Speckle Holography for High−Contrast Imaging

Chris D. Koresko

Interferometry Science Center (ISC)

Speckle holography is an observational technique which relies on the presence of a PSF calibration star in the same field as the target of interest to produce images of diffraction−limited resolution and high dynamic range. The observations are simple and efficient, and do not require any specialized hardware beyond an imager capable of being read out fast enough to "freeze" the atmosphere (i.e., frame time ~ 100 msec in the near−IR) and an image scale sufficiently fine to Nyquist sample the telescope's diffraction limit. This poster presents a study of the real−world performance of the technique when used on the 10 m Keck 1 telescope, and describes its application to the study of pre−main sequence visual binary stars.

Introduction

The uncertainty in the Point−Spread Function (PSF) is frequently the factor which limits the dynamic range in a high−resolution image. The PSF is sensitive to the precise behavior in the optical system, which is frequently time−dependent. For ground−based observations, the strong and rapidly−changing distortions caused by Earth's atmosphere are usually the main culprit.

Speckle Holography is an observational technique which attempts to sidestep this problem by selecting targets which have pointlike companions within an isoplanatic distance on the sky. The companion serves as a reference star, permitting the direct measurement of the PSF, whose imperfections can then be removed from the image using Fourier deconvolution.

Requirements

The optical system must produce sufficiently high magnification to Nyquist–sample the diffraction–limited image, *i.e.,* the pixels must be smaller than $\lambda/2D$, where λ is the observing wavelength and D is the diameter of the telescope.

The PSF must be relatively stable during the exposure of the image. This tends to preserve high spatial frequency power, allowing the deconvolved frames to have good signal–to–noise ratios at all frequencies less than the diffraction limit of the telescope.

The image of the reference star must be well separated from that of the science target, and they must lie within the same isoplanatic patch (*i.e.,* they must have the same PSF).

Holography from the Ground

Holographic observations made from the ground consist of numerous short-exposure frames which are comparable to the coherence time of the atmosphere, so that they sample individual realizations of the atmospheric PSF. In practice, the observational strategy for holographic imaging is similar to that for the more widely used technique of speckle interferometry.

Groundbased holography generally works best in the near–infrared, where the signal–to–noise available in each atmospheric coherence time is generally better than at visible wavelengths. The isoplanatic angle is typically 30 arcsec, which is larger than the size of a Nyquist–sampled array detector on a large telescope. The target and reference star must be sufficiently far apart that their *seeing–limited* PSFs are well separated.

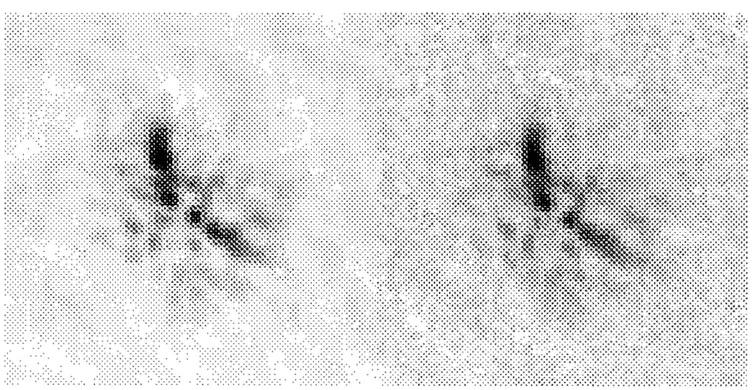
The need for short exposure times limits the technique to $K<10$ unless an adaptive–optics system is used.

Holography at Keck

Holographic imaging has been used successfully with the Near Infrared Camera (NIRC) at the 10 m Keck 1 telescope since 1997. The NIRC Image Converter is used to magnify the pixel scale to 20 mas/pixel, which is sufficient for Nyquist sampling at 2 μm. The diffraction limit of the 10 m telescope at this wavelength is ~50 mas.

The camera is rotated so that its readout direction lies along the line joining the target and reference star. This insures that the time between the measurements of the two objects is minimized, so that their measured PSFs are nearly identical. Because the PSF is measured frequently, there is no need to turn off the Keck image derotator as is done for speckle interferometry.

A Single Frame



This is a single 137−msec exposure on the pre−main sequence visual binary star Elias 2−26 in the Ophiuchus SFR. A complete reduction of this dataset, which consists of 857 such frames, indicates that both components are unresolved. Note the detailed similarity of the two stars' images.

The lower picture shows magnified subframes centered on the two stars. The brighter one is used as a PSF estimator to deconvolve the fainter one.

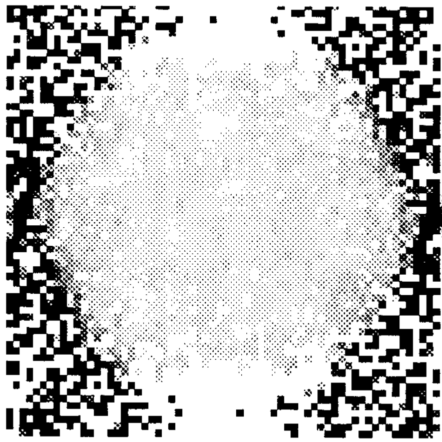
Data Reduction Process

The Fourier amplitude and phase are recovered separately. The amplitude processing is nearly identical to that used for speckle interferometry: The power spectra of the individual subframes are averaged, along with the power spectra of subframes containing blank sky. The average blank–sky power is subtracted from the averages of the target and reference–star power spectra, and the Fourier amplitude is the square root of the ratio of the sky–subtracted target power to the sky–subtracted reference power.

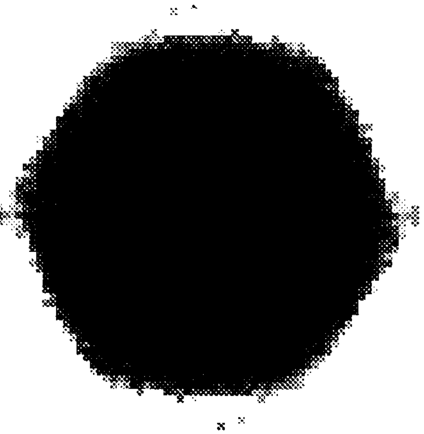
The Fourier phase is estimated for each frame as the difference of the phases of the target and reference–star images. This is simply averaged over the set of frames.

Errorbars are estimated from the scatter among the results derived from subsets of the data.

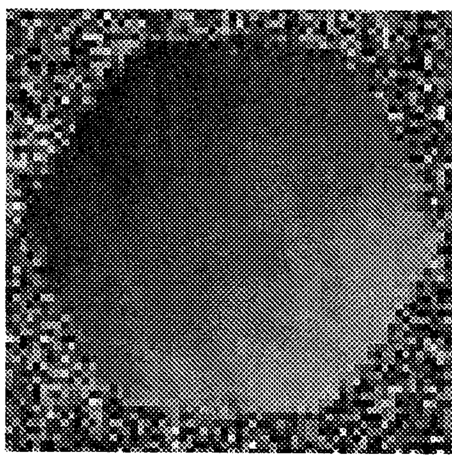
2D Power and Phase



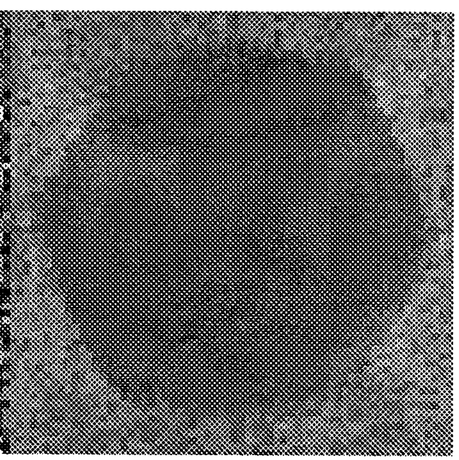
Power



Uncertainty



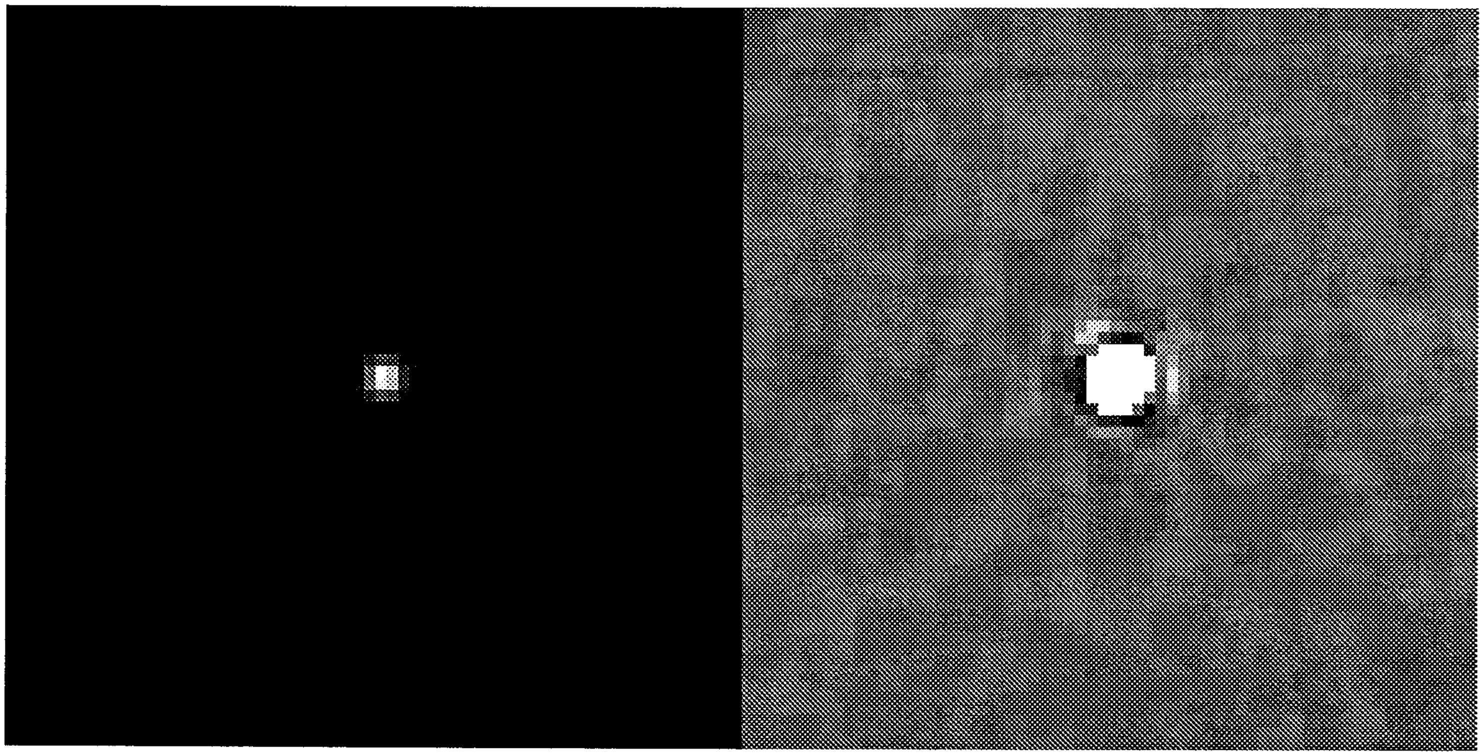
Phase



Uncertainty

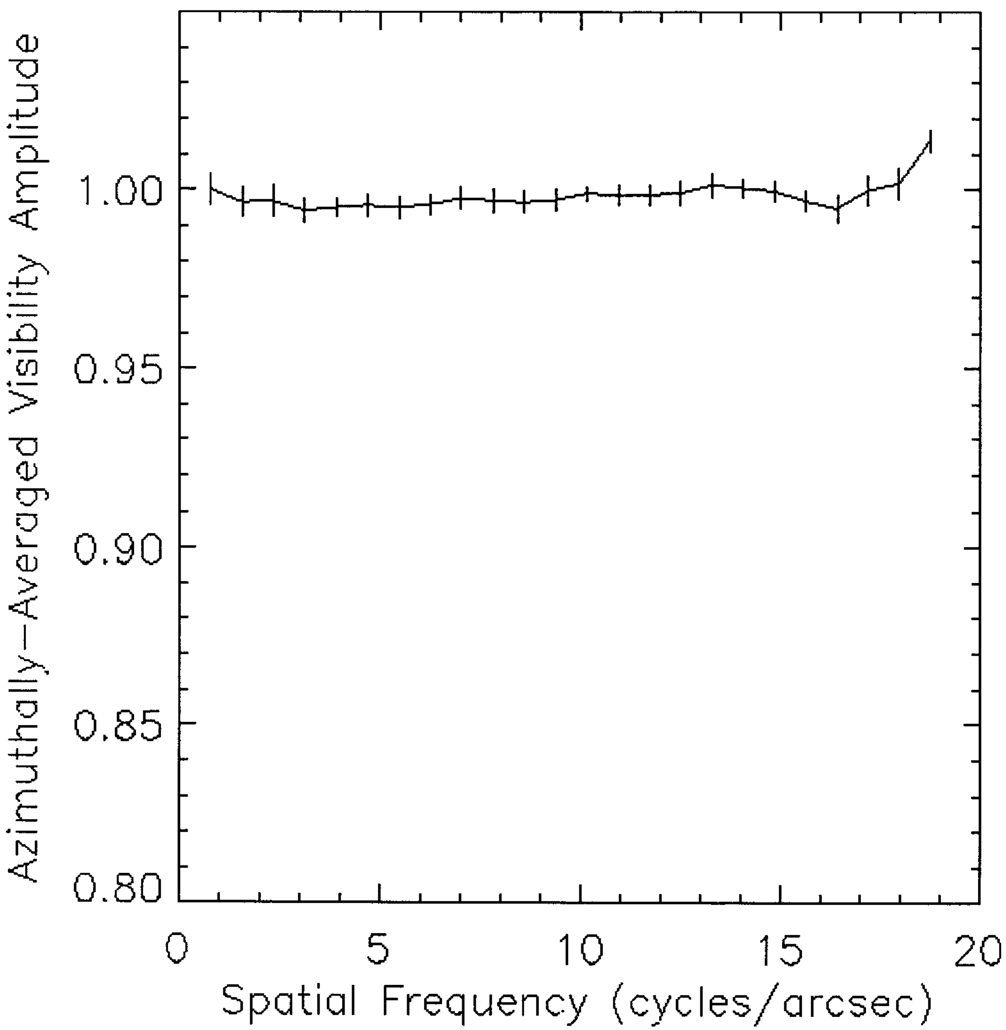
The two−dimensional Fourier transform components recovered from the whole set of frames. The zero−frequency elements are in the center. The data are meaningful within a hexagonal region defined by the shape of the Keck 1 primary. The slope in the phase is due to the separation between the stars not being equal to an integral number of pixels.

Reconstructed Image



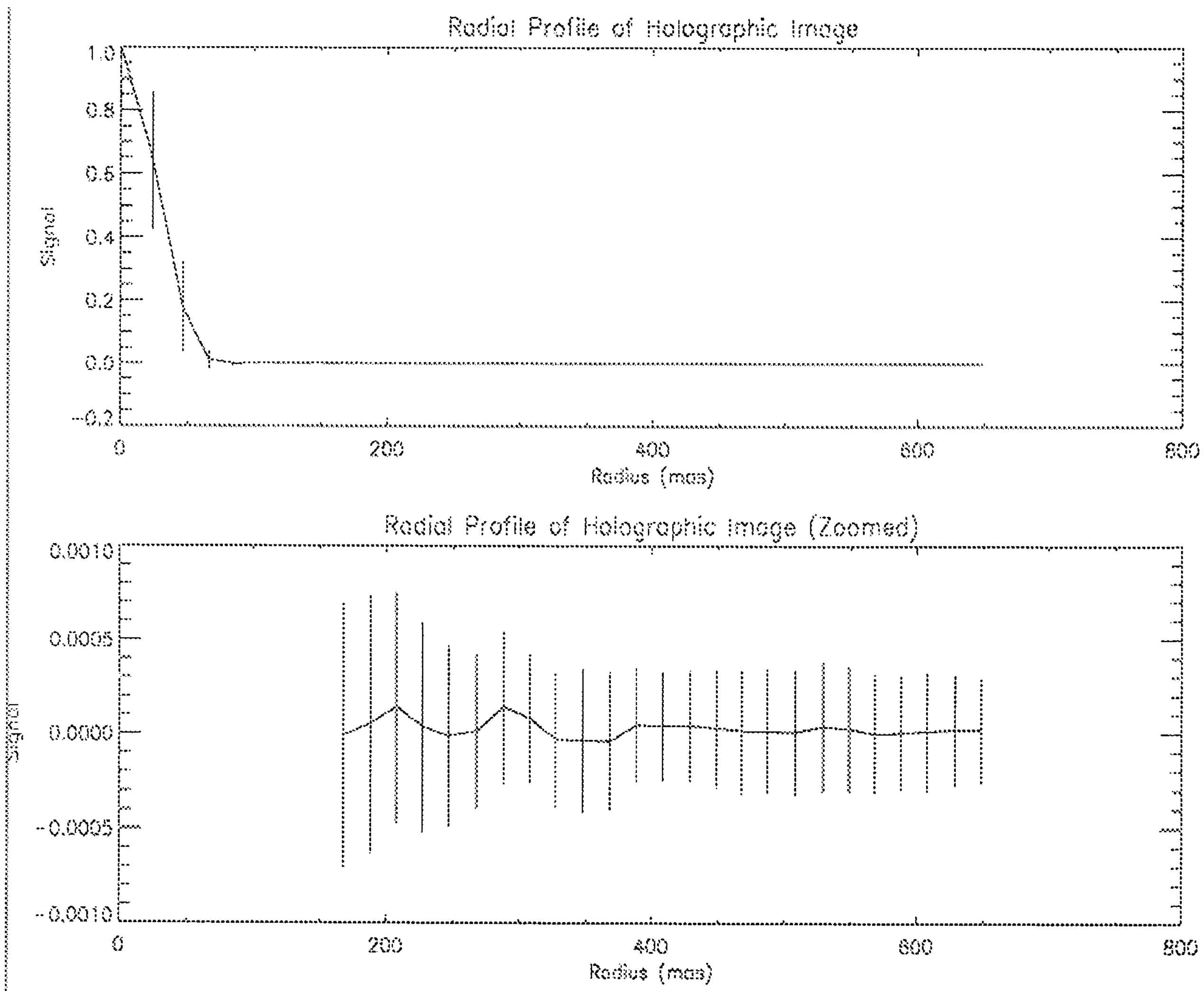
The holographic image of the target, reconstructed from the Fourier data by apodizing and simple Fourier inversion. The version on the right has been linearly stretched by a factor of 100 to make the noise visible. The FWHM resolution of the image is 55 mas.

Results for the Whole Dataset (cont)



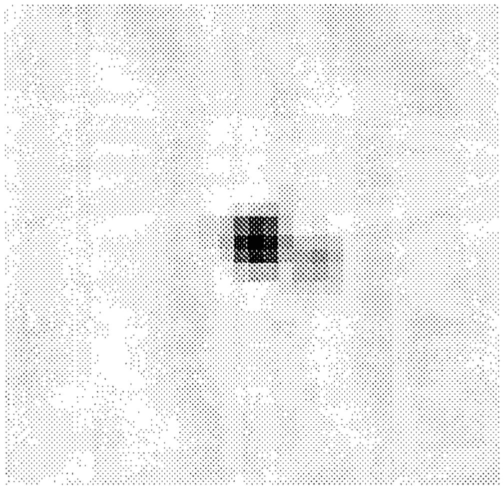
This plot shows the normalized amplitude of the Fourier transform of the reconstructed image. It has been reduced to one dimension by averaging over frequencies with nearly equal magnitudes. If the target were resolved, the curve would decline at high frequencies; instead, it is constant to within the noise.

Radial Brightness Profile

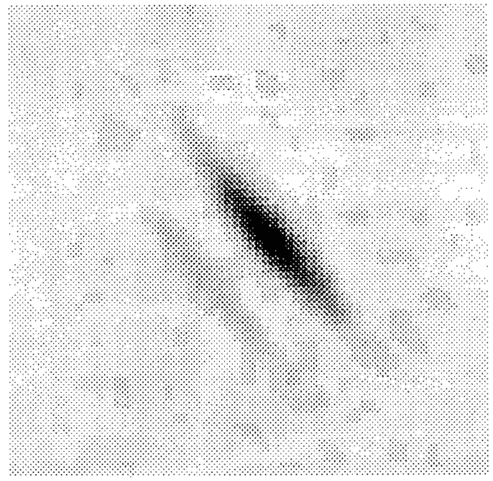


The brightness of the reconstructed image, averaged over pixels of equal distance from the star, gives an indication of how well the PSF is controlled. The dynamic range is >2000 at radii beyond 300 mas. The plateau at that distance points to read noise as the limiting factor.

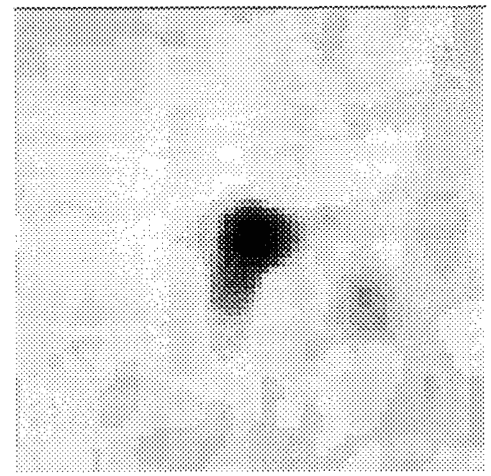
Application to Pre–Main Sequence Stars



T Tauri S (ab)



HK Tauri B



Haro 6–10 IRC

Published holographic images of the mysterious "infrared companion" to T Tauri reveal it to consist of a pair of stars separated by ~0".07, which the companion to HK Tauri is seen to be surrounded by a nearly edge–on circumstellar disk. The infrared companion to the T Tauri star Haro 6–10 is surrounded by a bright, compact nebula of complicated morphology.

Conclusions

Holographic imaging has demonstrated a dynamic range >2000 within 300 mas of the star. It requires only an imager with a suitable pixel scale and capable of acquiring frames fast enough to "freeze" the seeing.

The basic concept is simultaneous measurement of the target and its PSF. This approach should be applicable whenever a suitable reference star is available.

The next logical step is to use an adaptive–optics system as a "front end" for holographic imaging. This should permit improved sensitivity (because longer exposures are possible) and dynamic range (because less light goes into the speckle pattern).