Kernel-Phase Interferometry for Super-Resolution Detection of Faint Companions

The University of Texas at Austin

Samuel M. Factor, Adam Kraus

Dept. of Astronomy, The University of Texas at Austin

Background

The detection of companions to stars – both planets and stellar binaries – has traditionally relied on three methods: radial velocities (RVs), transits/eclipses, and direct imaging.

- Transit and RV surveys are insensitive to companions at large semimajor axes.
- While direct-imaging surveys are more sensitive to such objects, **there is often a gap between these two regimes, inside the inner working angle of direct imaging and outside the regime where transits and RVs can efficiently survey.**
- Imperfections in the optical path (and AO correction for ground based telescopes) introduce "speckles" which can be misinterpreted as companions.
- These speckles can be corrected using ADI, SDI, and LOCI at large angular separations, but those methods fail near λ/D.
- Interferometric analysis takes advantage of the wave nature of light and can be used to reject speckle noise and detect companions with high contrast *at or even below* the diffraction limit. **Rather than subtracting off the PSF, these techniques uses the information contained in it to infer the geometry of the source.** The discovery of the newly forming giant planet LkCa15b by Kraus & Ireland (2012) demonstrates the power of such techniques.

Filling the gap between RV and transit surveys and classical direct imaging surveys would offer a crucial new view of both stellar multiplicity and exoplanetary systems.

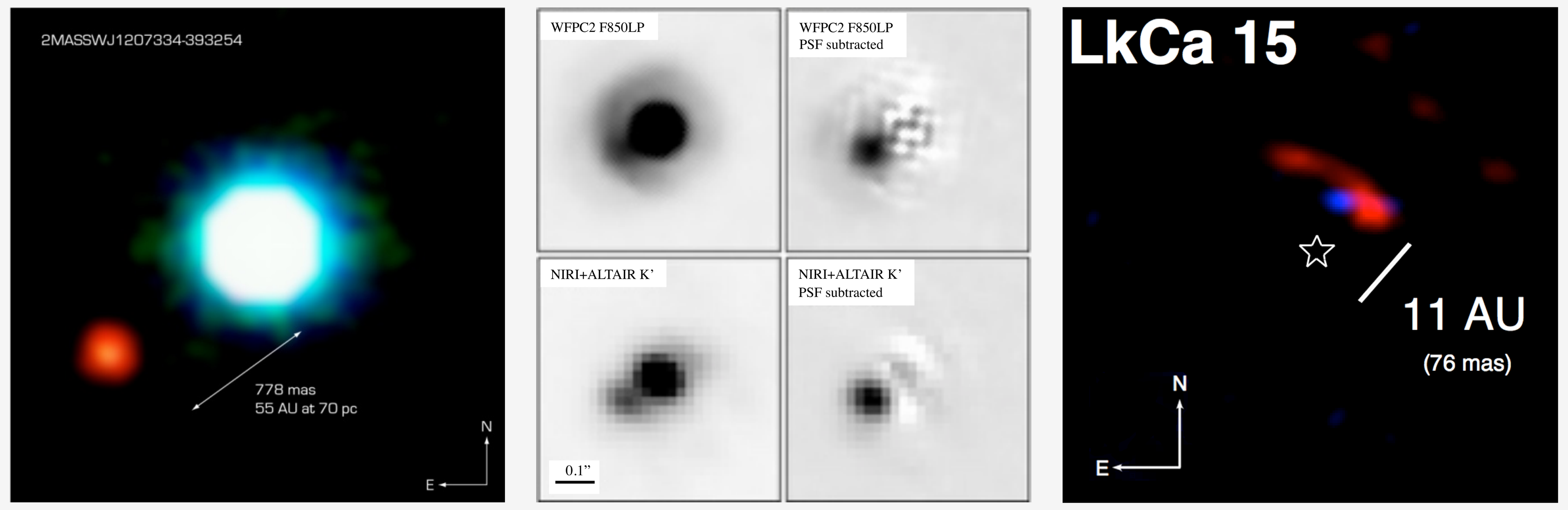


Figure 1: Examples of previously imaged low-mass companions. *Left*: VLT NACO image of 2MASS 1207AB, a brown dwarf with a ~7 M_{Jup} companion at ~55 AU (Chauvin et al. 2004). *Center*: WFPC2 and NIRI+ALTAIR raw and PSF subtracted images of the young brown dwarf 2MASS J044144 with a 5-10 M_{Jup} companion at 15 AU (Todorov et al. 2010). *Right*: Keck NRM K' (blue) and L' (red) band reconstructed images of LkCa 15b, a ~6 M_{Jup} companion at ~20 AU inside the gap of a transitional disk around a ~2 Myr old solar analogue (Kraus & Ireland 2012).

What is a Kernel-Phase?

Non-redundant masking (NRM) interferometry, the most common interferometric analysis technique for single-aperture telescopes, places a mask in the pupil plane, transforming a large single aperture into a sparse interferometer.

- This mask only allows ~5% of the light to reach the detector, imposing a severe flux limit. Unmasked apertures would be preferable.
- **Kernel-phase analysis models the *full aperture* as a grid of sub apertures** (shown in Figure 2). This defines which spatial frequencies are sampled.
- Since we are interested in the source geometry, we examine the *phase* of the Fourier transform of the image

Each pair of apertures, or baselines, contributes both the true phase of the source and a phase error from each of the apertures. Combining all the baselines together, we can write a matrix equation for the measured phases:

$$\Phi = \Phi_\circ + \mathbf{A} \cdot \phi \qquad (1)$$

Where Φ is a vector of the measured phases from each baseline, Φ_0 is the true source phase, **A** is a matrix encoding the baselines, and ϕ is a vector of the phase errors from each aperture. Each column of **A** corresponds to an aperture while each row corresponds to a baseline.

To derive an equation which is independent of the phase errors we use singular value decomposition to calculate the kernel (**K**) of **A** such that:

$$\mathbf{K} \cdot \mathbf{A} = 0 \qquad (2)$$

We can then simply multiply both sides of Equation 1 by **K** to get

$$\mathbf{K} \cdot \Phi = \mathbf{K} \cdot \Phi_\circ + \mathbf{K} \cdot \mathbf{A} \cdot \phi$$
$$= \mathbf{K} \cdot \Phi_\circ \qquad (3)$$

This produces observables called kernel-phases which are independent of phase errors, similar to closure-phases used with NRM. **This technique can achieve similar detection limits to NRM in a fraction of the time and can be applied to dimmer sources where NRM is not feasible, as well as archival data sets.** It was first presented by Martinache (2010).

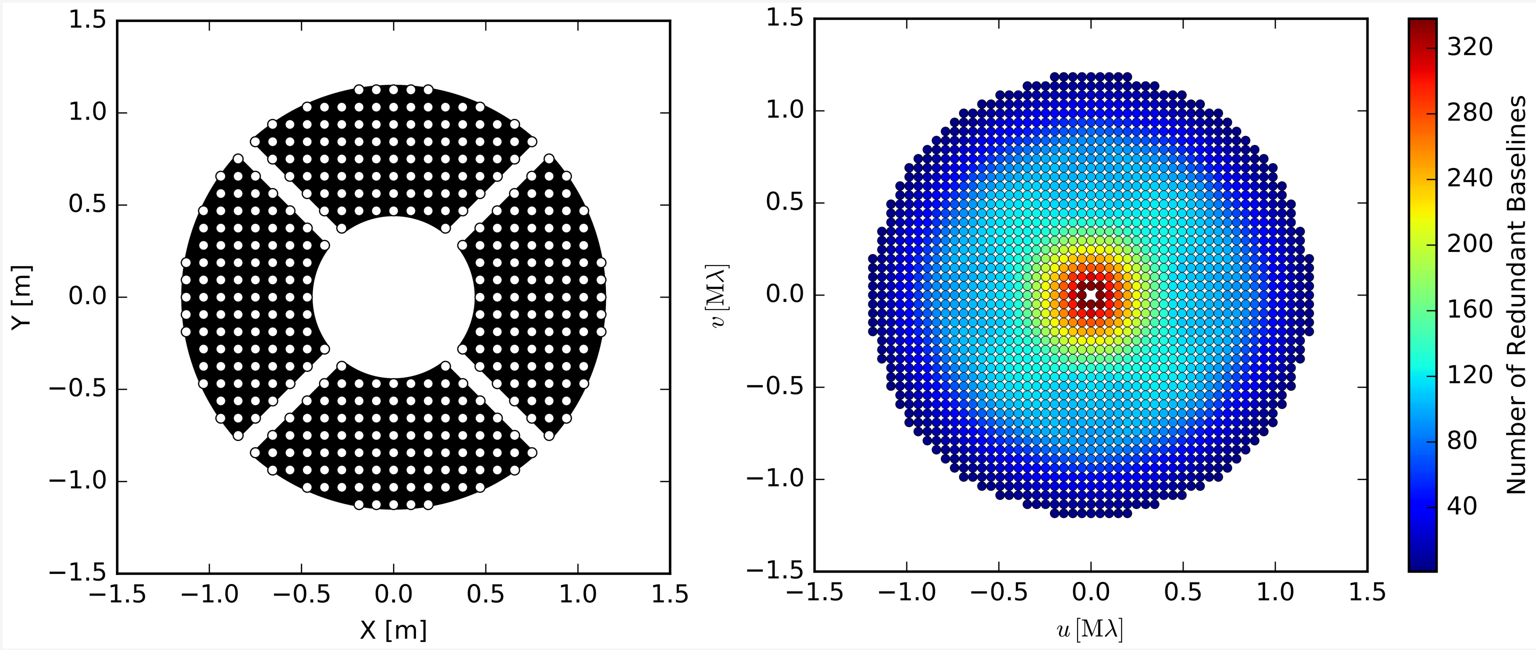


Figure 2: *Left*: Model HST aperture. *Right*: The corresponding baselines. Points are color-coded by the number of distinct pairs of apertures which contribute to the point. The 392 sub-apertures sample 938 unique baselines and generate 745 kernel-phases.

Results: A widely applicable pipeline for analysis of archival observations

We apply an MCMC analysis to the kernel-phases (using `emcee`; Foreman-Mackey et al. 2013) , fitting a simple 3 parameter (separation, position angle, and contrast) double point source model. First the source is located with sub-pixel accuracy. The image is Fourier transformed and shifted so that the flux centroid is at the center of the image. Phases are then sampled at the points defined by the aperture model (see Figure 2) and kernel-phases are constructed by multiplying by the transfer matrix. To fit the data, model kernel-phases are similarly calculated from *analytically* computed phases. Below is a simple test case showing a binary brown dwarf observed by Reid et al. (2006). We are working to apply this technique to other observations from HST NICMOS1 and ACS/HRC to search for close in binary and possibly triple brown dwarf systems as well as young high mass planetary mass companions.

Figure 3: *Top left*: HST NICMOS1 (F110W) image of 2MASS 0700+3157. *Bottom row*: Fourier amplitude (left) and phase (right). Grey circles show the sampled points. *Top right*: kernel-phases calculated from the sampled phases. A single point would have kernel-phases of 0° (with some small spread). This is clearly not the case, indicating the presence of a binary.

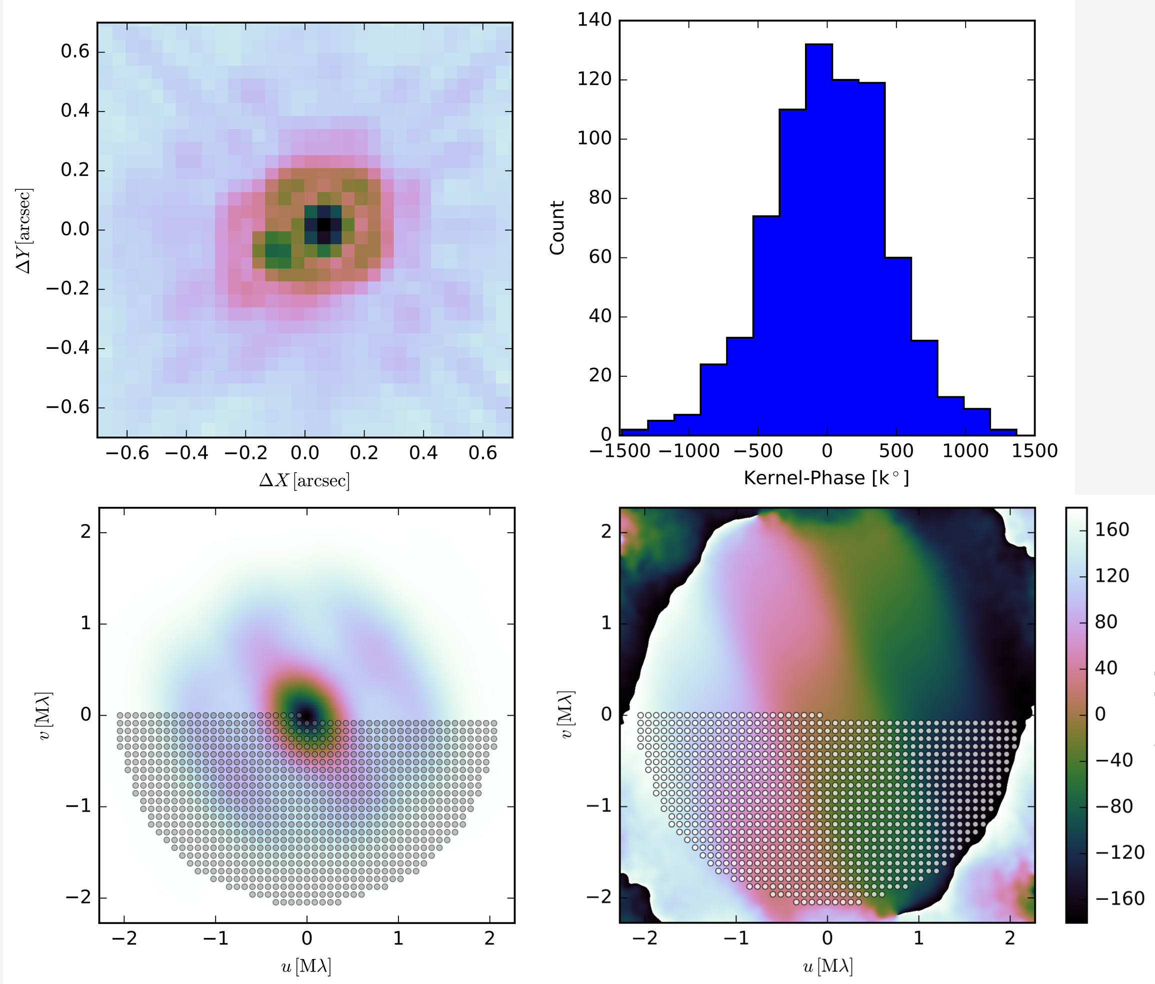
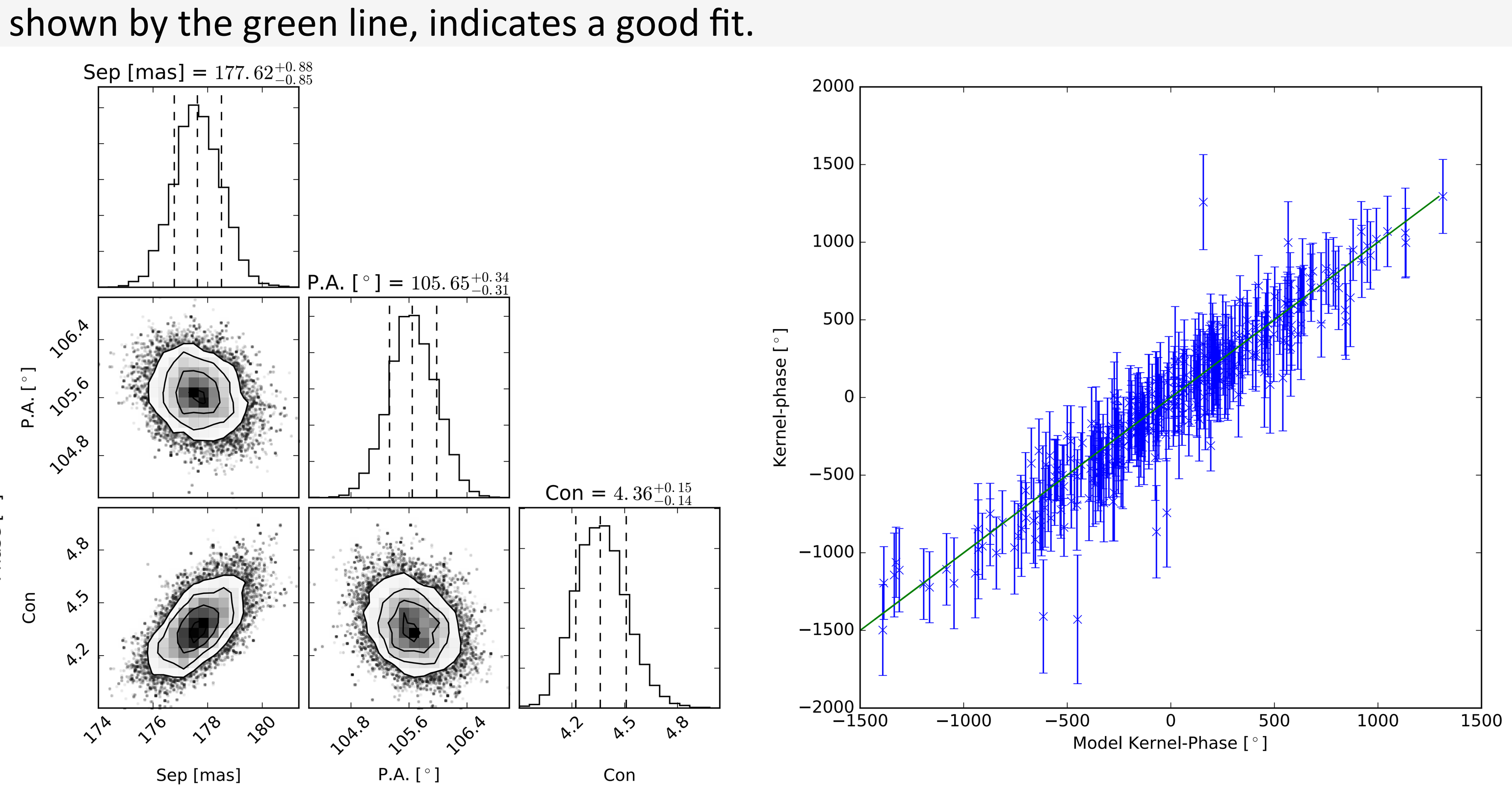


Figure 4: Results of fitting a simple double point source model. *Left*: Corner plot showing the 1- and 2D posteriors of the three parameter fit. *Right*: Kernel-phases generated from the image plotted against those from the best fit model. A 1-to-1 correlation, shown by the green line, indicates a good fit.



References and Contact Info.

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smfactor.github.io

Contact Info:

sfactor@astro.as.utexas.edu

The University of Texas at Austin
Department of Astronomy
2515 Speedway, Stop C1400
Austin, Texas 78712

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