

# Locally Optimized Combination of Images (LOCI) Algorithm

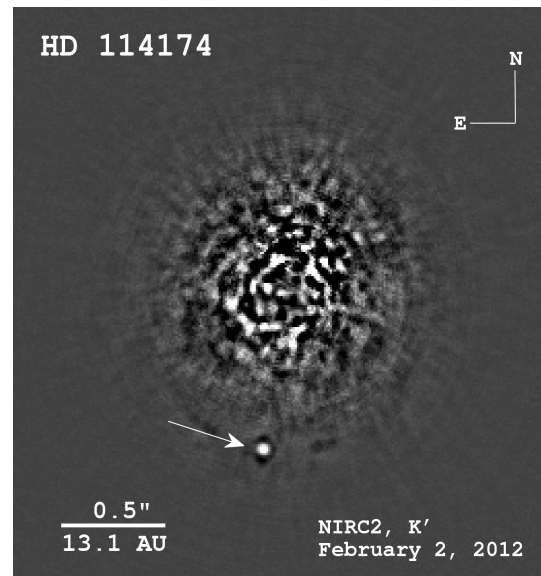
Keck NIRC2 Implementation using Matlab

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**1. INTRODUCTION** Of the myriad post-processing techniques used to reduce high-contrast imaging data, the Locally Optimized Combination of Images (LOCI) algorithm represents an intuitive and easy-to-code method that first showed significant improvements over standard image subtraction (Lafreniere et al. 2007). Rather than using a single point-spread function (PSF) reference to subtract unwanted starlight from a given high-contrast frame, it is possible to use a substantive library of reference images to reduce residual scattered light at small angular separations by generating an optimized reference image that well-matches the spatial distribution of speckles to be removed. The reference frame is constructed locally, i.e., in various sections and subsections of an image, using a linear combination of library frames. The end result is a factor of several improvement in effective contrast at the expense of only a marginal reduction (tens of percent) in overall off-axis throughput – that is reduction in the amount of light detected from a faint companion planet or brown dwarf orbiting the target star.

The purpose of this tutorial is to introduce you to the LOCI algorithm by providing step-by-step instructions for reducing on-sky AO imaging data. Raw .fits frames used for the tutorial are taken from an original data set acquired with the Keck II telescope on 2012 February 02 UT that resulted in the discovery of HD 114174 B (Crepp et al. 2013). **The companion is  $\Delta K=10.75$  magnitudes fainter than its parent star and separated by 0.7 arcseconds; it cannot be detected without using PSF subtraction.** In this implementation, the angular differential imaging (ADI) technique was used to help discriminate between stellar speckles and scattered starlight by allowing the background field (the sky) to rotate relative to a fixed instrument orientation (Marois et al. 2006).

**Fig. 1** – *Discovery image of HD 114174 B taken with NIRC2. We will employ the LOCI algorithm to reproduce this figure starting from a set of PSF reference frames.*



After completing all of the steps involved in running the Matlab reduction pipeline, you should be able to reproduce a lower S/N version of the image shown in Fig. 1 [due to time constraints we will use only a fraction of the data set]. The goals of the tutorial are as follows:

- become familiar with high-contrast imaging data
- understand angular differential imaging and implementation
- learn Matlab basics
- understand key features of LOCI algorithm
- develop some intuition for processing astronomical images
- generate publication-quality images using the Matlab GUI

Before running the image reduction program, it is worth briefly reviewing some of the basics about NIRC2 and the selection of Matlab for astronomical data processing.

**2. NIRC2 BRIEF DESCRIPTION** NIRC2 is an infrared imaging camera designed and built for the Keck II telescope on Mauna Kea. The instrument PI, Keith Matthews, works at Caltech. NIRC2 has 1024 x 1024 pixels and operates in the YJHKLM bands (from 1-5  $\mu\text{m}$ ). A variety of other narrow-band filters are also available. Operating behind the Keck II AO system (Wizinowich 2000), NIRC2 provides diffraction-limited observations with the ability to select one of three plate-scales (10, 20, 40 mas/pix), which correspond to progressively larger FOV. The “narrow camera” setting, i.e., 10 mas / pix platescale corresponding to a 10” x 10” FOV, is nominally used for high-contrast imaging (Crepp et al. 2012).

Observations that aim to maintain a fixed orientation on the sky (e.g., such that north is always up and east to the left) are executed in “position angle” mode. To allow the field of view to rotate throughout the course of an observation, NIRC2 may instead be placed in “vertical angle” mode by simply typing commands into a terminal window. Thus, with only a few button pushes, it is possible to perform angular differential imaging which provides “speckle diversity” to help remove bright speckles through post-processing.

More details about NIRC2 can be found here: <https://www2.keck.hawaii.edu/inst/nirc2/>

**3. MATLAB** Matlab is a well-documented and highly intuitive programming language with easy-to-understand syntax and powerful scripting capabilities. Its straight-forward (high-level) implementation style and GUI allow the user to concentrate on astrophysics instead of becoming bogged down with the idiosyncrasies of computer programming. Matlab has also developed a comprehensive list of rigorously tested functions (such as the Fourier transform) to facilitate common astronomical data reduction procedures. Further, numerous tutorials are available on the web, and the vast majority of universities with science and engineering departments have already invested in Matlab by purchasing licenses in bulk to provide direct access to students, postdocs, and professors, including remote log-in. Finally, Matlab understands Linux commands and serial code may be converted into parallel code to run on multiple CPU’s within a matter of minutes(!)

You can find numerous other useful Matlab commands and scripts here:

<http://www.mathworks.com/products/matlab/>

**4. LOCI IMPLEMENTATION** Assuming we have just collected a series of high-contrast images from Keck, how does one then use these frames to perform PSF subtraction? At its core, LOCI is a matrix inversion method that uses least-squares.

### DISCUSSION OF MATLAB LOCI KERNEL CODE

**5. THE CURIOUS CASE OF HD 114174 B** Let's now move on to an example using on-sky data. First, some relevant background information: HD 114174 B is a very faint companion discovered serendipitously by the TRENDS high-contrast imaging program (Crepp et al. 2013). Its intrinsic brightness and neutral NIR colors initially fooled your instructor into thinking that the object was a brown dwarf. However, a dynamical mass constraint precludes such an interpretation: HD 114174 B is in fact a compact object – an old white dwarf. [Thus the “secondary” used to be brighter than the primary!]

Detailed inspection of the companion properties also reveals an apparent age discrepancy between HD 114174 B and its parent star (Matthews et al. 2014). Did these two objects (the primary and secondary) not form at the same time? Or are other physical processes at work giving the impression that the ages differ when they are in fact the same? The above mystery is still outstanding ...

**6. HANDS-ON EXERCISE** Table 1 shows a copy of the NIRC2 observing log from 2012 Feb. 02. You can read the top line of the log sheet to decipher pertinent information including file names, filter used, seeing conditions, integration time, camera mode, etc.

*Can you identify which frames were used to establish PSF reference images?*

*Why is the integration time in Row 2 longer than in Row 1?*

*Approximately how much field rotation was achieved in total?*

*How does field rotation relate to inner-working angle and integration time?*

NIRC2 Log														
UT Date <u>Feb. 2, 2012</u>			Data Directory _____			SA _____			OA _____					
Conditions _____			Observer _____			Page <u>4 / 4</u>								
File number	Script	Object	Time	Filter	Cam	Pupil	Tint	Coadd	#Reads	Compass	WFS	AO	Other	Comments
Start	End	Used	UT							rose	cnts	Rate		
813		bwb 0.5 n=2	13:58	K <sub>p</sub>	NAR	large hex	0.018	400	2	Slightly red				Very dim unocculted, size 256
819		30i					2	10		P <sub>0</sub> :-31.6 P <sub>1</sub> :+8.6	Seeing 2	0.62"		occulted
911		bwb 2 n=3	14:55				0.3	50						positioning E

**Table 1** – Copy of observing log from 2012 Feb 02 involving the discovery of HD 114174 B. We will use a fraction of these images to recover the companion.

Let's open the Matlab GUI to get started.

[1] If necessary, unzip the files matlabcode.zip and adi\_data.zip in the current working directory: /ssw/Tue/Part2/

[2] Start the program and GUI by typing from the terminal command line: matlab &

[3] If necessary, use your cursor to select a convenient directory for running the Matlab code by modifying the "Current Folder" entry near the top of the screen.

Please note that in the following the NIRC2 data has already been: flat-fielded, hot pixels cleaned, Fourier filtered, and \*aligned\* with precision.

Create first reference image using LOCI.

[4] Define the size in pixels of the large and small boxes used for PSF comparisons. Type into Matlab GUI command line:

```
>> dL=27; % Specify size of local region for comparing PSF's.
```

```
>> jump=7; % Specify size of small region for actual PSF subtraction.
```

[5] Load relevant "science" files (i.e., images containing purported companion):

```
>> science1=fitsread('HD114174_science1.fits');
```

```
>> science2=fitsread('HD114174_science2.fits');
```

```
>> science3=fitsread('HD114174_science3.fits');
```

... in practice there will be several dozen or hundred science files.

[6] Now load a cube of images for constructing an optimal reference frame:

```
>> refcube1=fitsread('HD114174_reference_cube1.fits'); % Large file.
```

This step may take a minute ... we can upload the remaining reference cubes later.

You can use the program ds9 to view the data cube and science .fits images by typing:

```
ds9 filename.fits
```

into the linux command line.

[7] Use your cursor to open the LOCI\_Sagan\_workshop.m file into the Matlab GUI. After viewing the code (and discussing the algorithm as a class), identify the program inputs. We are now ready to create our first reference image.

```
>> ref1=LOCI_Sagan_workshop(science1,refcube1,dL,jump);
```

**[8]** Subtract optimal reference frame from science image:

```
>> Result1=science1-ref1;  
>> Result1=conv_w_gauss(Result1); % Optional Step: Can smooth data at pixel level.
```

**[9]** Plot results:

```
>> figure(1)  
>> imagesc(Result1)  
>> axis equal tight  
>> colormap(gray)  
>> colorbar('vert')  
>> set(gca,'YDir','normal')
```

**[10]** Change image display scale to search for HD 114174 B by eye:

```
>> imcontrast(1) % Toggle intensity cut-off bounds using imcontrast window
```

The companion can just barely be noticed at 5 o'clock position – must stack more data!

**[11]** Wash, rinse, repeat using more science frames then co-add results:

```
>> ref2=LOCI_Sagan_workshop(science2,refcube2,dL,jump);  
>> Result2=science2-ref2;  
>> Result2=conv_w_gauss(Result2); % Removes "salt-pepper".  
>> figure(2)  
>> imagesc(Result2)  
>> axis equal tight  
>> colormap(gray)  
>> colorbar('vert')  
>> set(gca,'YDir','normal')  
>> imcontrast(2) % Again toggle display intensity scale to identify companion.
```

**[12]** Repeat above procedure to produce Result3.

**[13]** Finally, stack results to demonstrate increased S/N and unambiguous detection:

```
>> Final=Result1+Result2+Result3;  
>> figure(4)  
>> imagesc(Final)  
>> axis equal tight  
>> colormap(gray)  
>> colorbar('vert')  
>> set(gca,'YDir','normal')  
>> imcontrast(4)
```

[14] Some fodder for class discussion:

Why is HD 114174 B not at the same azimuthal angle as shown in Fig. 1?

Why is the S/N low compared to Fig. 1?

Why does the S/N improve upon stacking – I thought the sky was rotating?!

How would one calculate a reliable flux ratio?

### **REFERENCES**

Marois et al. 2006, ApJ, 641, 556, *Angular Differential Imaging: A Powerful High-Contrast Imaging Technique*

Lafreniere et al. 2007, ApJ, 660, 770, *A New Algorithm for Point-Spread Function Subtraction in High-Contrast Imaging*

Crepp et al. 2013, ApJ, 774, 1, *The TRENDS High-contrast Imaging Survey. III. A Faint White Dwarf Companion Orbiting HD 114174*