Angular Differential Imaging with Microwave Kinetic Inductance Detectors

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The MKID arrays, developed and used in the Mazin Lab at UCSB, are highly specialized IFUs designed to detect faint sources on the sky. To increase the potential of uncovering faint sources in the MKID data, such as exoplanets, a step implementing a noise reduction technique called Angular Differential Imaging (ADI) will be appended to the MKID data reduction pipeline. ADI takes advantage of the rotation of the sky to help differentiate between a true point source of interest and noise introduced by the imaging system.

I. INTRODUCTION

A. Exoplanets

The past decade has been extremely exciting for exoplanet astronomy. Many new advances in technology have slowly allowed astronomers to gain the ability to consider directly imaging exoplanets around nearby stars to probe their characteristics, such as atmospheric composition and mass. Current methods to detect, image, and characterize nearby exoplanets, such as transit absorption spectroscopy, are less direct; the star/planetary companion must be at the correct orientation such that the companion blocks most of the light from the star during transit, allowing the thin atmospheric ring to be probed. One of the new detector technologies pushing the direct imaging horizon are the MKIDs developed in the Mazin Lab at UCSB. These sensitive detectors were designed specifically for imaging very faint sources on the sky, but the current instrument that utilizes the technology, The MKID Exoplanet Camera (MEC), is connected to the ground-based Subaru telescope, implying that there will be quasi-static speckle noise in the resulting data due to atmospheric effects and unavoidable imperfections in the imaging system. This quasi-static speckle noise, in addition to noise introduced as a result of inoperable pixels on the detector array in MEC, can obscure faint companions. Angular Differential Imaging is a noise reduction technique designed to mitigate the information loss due to this quasi-static noise.

B. MKIDs

Microwave Kinetic Inductance Detectors (MKIDs) are superconducting resonators that are used as the pixels within an integral field unit attached to UVOIR instruments. These detectors are ideal for imaging faint sources on the sky (E.g. exoplanets) because they are single photon detectors and have high read-out speeds.

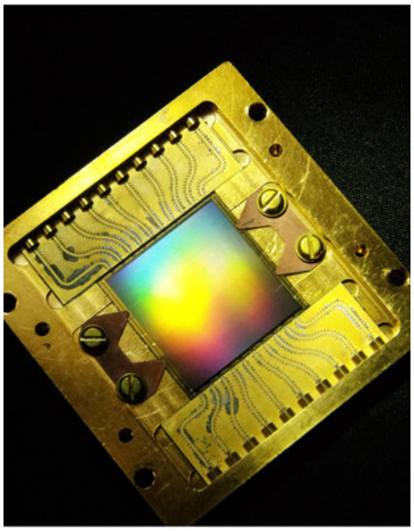

FIG. 1. ˜20000 pixel MKID array used as IFU in MKID Exoplanet Camera (MEC)

II. ANGULAR DIFFERENTIAL IMAGING

A. What is ADI?

Angular Differential Imaging is a noise reduction algorithm used to attenuate or remove quasi-static noise from observation data with the goal of uncovering faint companions that may be obscured. It takes advantage of the fact that with the de-rotator on an altitude-azimuth mounted telescope disabled, the FOV, from the perspective of the imaging detector, will rotate. Aberrations sourced from the imaging system, such as small fluctuations in the optics due to temperature changes, will evolve slowly and remain mostly fixed while true point sources on the sky will rotate around the FOV with a known trajectory, based on the target's location on the sky, location of the telescope, and the angular separation of the point source from the target.

III. IMPLEMENTATION

A. MKID Pipeline

The MKID pipeline is a data reduction software package that takes raw data from MKID equipped instruments and transforms it into a baseline state such that data analysis on the output can then be performed. The ADI implementation will be integrated as a pipeline post-processing step; it's not required when running the pipeline and will only be used for specific observations, due to the field-of-view (FOV) rotation requirements that will be discussed later. ADI also needs the output format of the reduced data to be subdivided into sequential frames (images) to take advantage of the previously mentioned FOV requirement. This enables us to design the ADI implementation to take output data from the pipeline as input, which will decrease the total computation time since the pipeline will only need to be executed once in the scenario that the parameters to tune the ADI algorithm, for a given observation, need to be changed.

B. Classical ADI Algorithm

The Angular Differential Imaging (ADI) technique has gone through many iterations to increase effectiveness since its inception, but we decided to use "Classical ADI" as implemented in the Vortex Image Processing Package for High-contrast Direct Imaging (VIP), using the original algorithm proposed by Marois et al [1][2]. The algorithm is broken down into three primary steps, the first of which begins with generating a reference point spread function (PSF) that models noise generated by the detector by median combining all n frames from the observation. This reference PSF is then subtracted from each frame in the observation. Because of the rotation of the FOV, the point source of interest should be left mostly intact after this subtraction while the pixel-to-pixel noise (noise generated by the detector), which is well represented by the median, is removed. In general, the frames from the observation are defined by a time, t, and an angle, θ. θ_i is defined as the angle that corresponds to the FOV rotation at time t_i. Each frame, I_i, can then be defined as a function of t_i and θ_i [1]:

$$I_i = I_i(t_i, \theta_i) \tag{1}$$

The first step can then be defined as

$$I_i^{sub} = I_i - med(I_1, I_2, I_3, ..., I_n) \tag{2}$$

where I_i^{sub} is the residual frame after having the reference PSF subtracted. The second step aims to reduce quasi-static noise by generating a localized reference PSF for each frame by only considering surrounding frames that have had sufficient FOV rotation such that a point source has a displacement between the two inner frames of at least 1.5 full-width, half maximum (FWHM) of the observing instrument. This decreases the chance of including information from the point source in the localized reference PSF, minimizing unwanted subtraction, while increasing the chance of removing noise with shorter lifetimes. The surrounding frames are then median combined to form the localized reference PSF and subtracted from the candidate frame. To allow the algorithm generalize to having point sources at many different separations in the same image, the frame is broken up into many annuli and then the process is repeated, per annulus. This is shown in Fig. 1. The per annulus process is defined in Eqn. 3, where I_i^{loc} is the annular residual for the given frame after the localized median subtraction, a is a normalization factor, and b and c are intervals in the frame sequence such that the reference frames have sufficient separation from the candidate frame.[1]

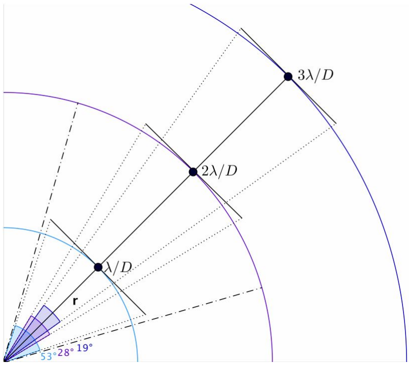

FIG. 2. Diagram depicting frame exclusion zone, in degrees, based on annulus radius due to insufficient FOV rotation [2]

$$I_i^{loc} = I_i^{sub} - a \times med(I_{i-b-1}^{sub}, I_{i-b}^{sub}, I_{i+c}^{sub}, I_{i+c+1}^{sub}) \tag{3}$$

The final step derotates all of the residual frames from the first two steps such that the FOV all frames align with the initial frame. The resulting image is then generated by median combining all of the derotated frames, defined by Eqn. 4 [1].

$$I = med(I_1^{loc}, rot(I_2^{loc}, \theta_{1-2}), ..., rot(I_n^{loc}, \theta_{1-(n-1)})) \tag{4}$$

IV. RESULTS

A. Astronomical Target Choice

The target that we used for this project is suspected to have an unpublished companion (at the time of this writing) and also had ideal seeing conditions during the time of observation. Even though there is a suspected companion associated with this target, we decided to first try and quantify the contrast improvement from the VIP

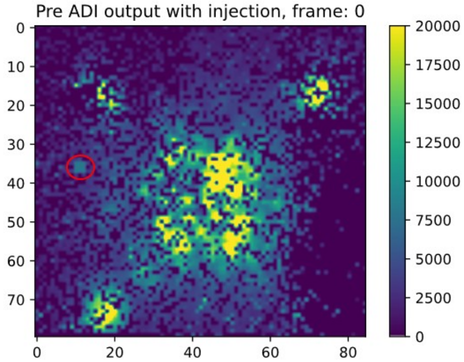

FIG. 3. Initial reduced, pre-ADI frame of dataset with injected companion

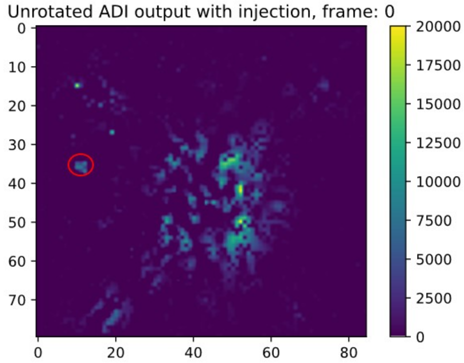

FIG. 4. Initial reduced, post-ADI frame of dataset with injected companion

ADI implementation on MKID data by injecting a simulated companion into the reduced observation data. Because this was a first pass at using the VIP package, we initially only wanted a baseline, allowing us to simply define the composition of the injected companion to be uniform with a square shape. The frames in the FITS data cube that were used had a timestep of 20s while the simulated photon count of all pixels representing the companion was fixed at 8000. This gave a rate of 400 $\frac{photon}{s}$ per pixel. The companion was injected at a radial separation of 0.25", which put it slightly outside the most intense area of the central PSF. Figure 3 shows a plot of the initial frame from the observation data set with the injected companion. Due to the location of the telescope used for the observation, the total observing time of 1800s, and the target's location on the sky, we were only able to see approximately 20 degrees of FOV rotation.

B. Final Findings

Although we were unable to get a quantitative answer on the contrast improvement after applying ADI to a dataset this Summer, we were able to produce a proof-of-concept result showing that the technique can indeed recover injected companions in MKID data. Figure 4 shows the same frame from the observation data shown in Figure 3 after Phase 1 and Phase 2 of ADI. The central PSF and satellite spots that were present in Figure 3 have been greatly attenuated while the injected companion is still present. The final image, after derotation and median combination of all frames in the dataset, is shown in 5. As expected, the companion is accentuated while the surrounding noise has been greatly reduced. We believe that if we can perform an observation with longer total exposure time, the total amount of FOV rotation will increase, allowing for fainter companions to be revealed.

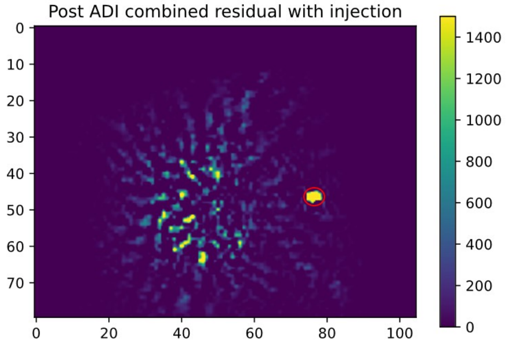

FIG. 5. Final post-ADI residual showing injected companion and attenuated noise

C. Future Work

Our initial implementation of ADI expects much of the pre-processing to be performed prior to execution. Some examples of this pre-processing are: centering of the target in the FITS frames, the calculation of the parallactic angles for each frame, and the concatenation of many FITS data cubes representing the entire observation into one cube. With the proper metadata, this pre-processing can be incorporated into the ADI class in the future to centralize all of the functionality. The MKID Pipeline currently has a software object defined, MKIDObservingDataset, that can be used to encapsulate this metadata and can be leveraged to simplify the parameters needed to instantiate an ADI object. A more experimental task for the future would be to determine the amount of FOV rotation necessary to uncover companions at certain separations and intensities. This has been explored in the existing literature but since ADI has not been used on MKID data, there is no first-hand baseline. Companion injection code more sophisticated than that used this Summer that accurately models real companions can be used to explore this, followed by observations of targets with similar characteristics.

ACKNOWLEDGMENTS

I would like to thank Ben Mazin for allowing me to join the lab this Summer. There is great work going on here on a variety of interesting projects involving MKIDs and I am sure there will be a large amount of good science that will follow in the upcoming years. I also would like to thank John (Jeb) Bailey and Sarah Steiger for being patient with me and being great sources of technical knowledge as I worked my way through understanding the MKID pipeline. This was key in allowing us to get the data we needed to implement and test ADI. A large thanks is also in order for my graduate mentor, Noah Swimmer, who was the guide in my initial foray into the field of Astronomy. The depth of his explanations and willingness to be hands-on with me proves that he will one day become an excellent teacher of Physics. Finally, I want to thank Sathya Guruswamy for coordinating a great remote research experience. The workshops provided practical knowledge and the physics talks were great windows into potential fields that can be explored in graduate school and beyond! This research experience was enabled by the NSF REU grant PHY-1852574.

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