

Planet signal extraction from direct imaging using common spatial pattern filtering

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Direct Imaging Standards

- Exoplanet imaging is difficult:
 - Faint signal
 - Significant noise
- The Current Standard: Principal Component Analysis (PCA)^(Wold, 1987)



PCA and Common Spatial Patterns^(Wang, 2005)

- Angular Differential Imaging^(Marois, 2006)
- PCA: $\frac{argmax}{w} \|Xw\|^2 \ s.t. \|w\| = 1$
 - Subtracting a least-squares approximation of an image from the image itself
 - Karhunen-Loève Image Processing (KLIP)(Soummer, 2012)

• CSP:
$$\frac{argmax}{w} \frac{\|X_1w\|^2}{\|X_2w\|^2} \quad s.t. \|w\| = 1$$









Jessica Donaldson astrobites, 2013

Problem Definition

- Let X_1 be all the images from one observing sequence
- Let X_2 be the same data, derotated
- Columns of X_n are single vectorized images



Solving
$$\underset{W}{argmax} \frac{\|X_1w\|^2}{\|X_2w\|^2} s.t.\|w\| = 1$$

1. Image–Image Covariance Matrices

$$S_n = \frac{X_n X_n^T}{p-1}$$

2. Composite Covariance Eigenvalue Decomposition

$$S = S_1 + S_2 = U_0 \Sigma U_0^T$$

- 3. Whitening Matrix $P = \Sigma^{-1/2} U_0^T$.
- 4. Whitened, Normalized Data

$$\overline{S_n} = PS_n P^T$$

Solving
$$\underset{W}{argmax} \frac{\|X_1w\|^2}{\|X_2w\|^2} s.t.\|w\| = 1$$

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$$\overline{S_n} = PS_nP^T$$

 $\overline{S_1} + \overline{S_2} = I$



Extracting the Planet Signal

 $\bar{S}_n = U\Sigma U^T$

 $Z = U^T P X_1$

 Z_k is final k rows from Z

Signal for a given target image t is $(Z_k^T Z_k)t$

Extracting the Planet Signal

 $\hat{S}_n = U \Sigma U^T$

 $Z = U^T P X_1$

 Z_k is final k rows from Z

Signal for a given target image t is $(Z_k^T Z_k)t$





Modes Overview

Original Image:



Maximum Eigenvalue



Eigenvalue ~ 0.5



Minimum Eigenvalue



Threshold - Too High, 0.05



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Threshold - Too Low, 0.002



Threshold - Just Right, 0.005



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Data Sources

- GPIES, Nov 2015, B Pic b
- Limited to ADI
- Repeated analysis on HD 1466
- Planetary Injection
 - 2D Gaussian fit to B Pic b
 - Same strength as B Pic b
 - Rotate with Parallactic Angle
 - 5 injected



Methodology

- Angular Separation
 - From inner ring to outer ring
 - Measurements averaged at given radius
 - Moving through noise regimes
- Varied signal strength
 - 0.5 to 4.5 percent of max value
 - Each set of 5 averaged together
- Iterated through different thresholds
 - Kept the strongest Signal-Noise Result



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Evaluation Metrics



Signal - Noise Ratio

$$SNR_{i,j} = \frac{S_{i,j}}{var(N)}$$

- Signal strength is peak of fit Gaussian
- Noise area is local section of annulus

Astrometric Biases

$$C[\tau_x, \tau_y] = \sum \sum S[x, y]T[x - \tau_x, y - \tau_y]$$

- Matched filter
- Point of maximum crosscorrelation

Signal to Noise Ratio

	//////////////////////////////////////	///////////////////////////////////////	///////////////////////////////////////		///////////////////////////////////////					1111111111111111	
610	- 3.5	4.5	5.8	7.6	8.5	8.8	9.2	9.4	9.5 -		0
570	- 3.8	4.6	5.7	7	8.1	9	9.2	9.5	9.6 -		9
520	- 3.6	4.1	4.8	5.6	6.3	6.8	7.9	8.4	8.7 -	-	8
(se 480	- 3.5	3.8	4.5	5	5.6	6.3	7	7.5	7.7 -		
ш ы 440	- 3.7	4.4	5.2	6	6.9	7	7.6	7.9	8.2 -	-	7
oarati	- 3.6	3.9	4.4	5.1	5.8	5.8	6.1	6.3	6.5 -	_	6
w 350	- 3.9	3.7	3.8	3.9	4	4	4.1	4.1	4.1 -		
300	- 4.2	4.1	4.1	4.5	5	5.1	5.4	5.7	5.9 -	-	5
260	- 4	4.2	4.7	4.9	5	5.1	5.2	5.4	5.7 -		
210	- 4	4.7	4.5	4.7	5	5	4.8	4.8	5.6 -		4

0.005 0.01 0.015 0.02 0.025 0.03 0.035 0.04 0.045

Injected Signal Strength

Centroiding Error

610 23 22 0.4 0.3 0.3 0.3 0.3 2.2 0.4 30 570 2.7 2.2 0.3 0.3 0.3 0.3 5.8 3.6 0.3 520 5.1 3.9 6.4 1.2 0.9 0.4 0.4 0.4 25 480 7.1 2.9 2.7 2.3 2.2 2.2 2.2 3.2 0.7 Separation (mas) 20 34.2 0.7 440 5.2 30.6 0.6 0.6 0.6 0.5 4 390 4.8 4.3 3.2 2.9 2.9 2.7 1.9 0.7 0.5 15 350 4.5 3.7 3.6 3.4 1.6 1.5 2.3 4 1 10 300 2.6 4.8 2.3 1.8 1.6 1.6 1.5 0.9 260 6.4 6.3 3.8 2.7 2.6 18.8 0.6 2.7 0.6 5 210 7.6 5.9 5.8 5.7 5.7 5.6 5.9 5.8 5.3 0.015 0.025 0.035 0.005 0.01 0.02 0.03 0.04 0.045

Injected Signal Strength

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2

1.5

1

0.5

0

-0.5

-1

-1.5

-2

-2.5

CSP - KLIP Comparison, Beta Pic

SNR

610	1.1	-2.9	-2.8	-1.7	-1	-0.8	-0.5	-0.3	-0.2		
570	- 0.1	-1.5	-2	-1.6	-1	-0.3	-0.2	0	0		
520	- 0.4	-1.1	-2	-2.1	-1.9	-1.6	-0.8	-0.4	-0.1		
्रि 480	- 0.4	-0.9	-1.2	-1.4	-1.2	-0.7	-0.1	0.2	0.5		
440	- 0.5	-0.3	-0.8	-0.8	-0.3	-0.5	-0.1	0.2	0.5		
390	- 0.2	0.4	0.1	-0.1	0.1	-0.1	0.1	0.2	0.2		
350	- 0.6	0.3	0.5	0.3	-0.1	-0.5	-0.7	-1	-1.2		
300	- 1.1	1.2	1.2	1.3	1.7	1.3	1.3	1.3	1.3		
260	- 0.7	0.9	1.6	1.5	1.6	1.4	1.1	1	1.1		
210	- 0.5	1.2	1.2	1.3	1.7	1.6	1.3	1.2	2.1		
0.005 0.01 0.015 0.02 0.025 0.03 0.035 0.04 0.045 Injected Signal Strength											

Centroiding Error

	610	29.3	21.8	2.1	0.3	0.3	0.2	0.2	0.2	0.3 -	
	010	20.0	21.0		0.0	0.0	0.2	0.2	0.2	0.0	
	570	- 0.7	3.2	2.5	2.1	0.2	0.2	0.2	0.2	0.2 -	
	520	41	0.4	6.2	1	0.9	0.8	0.3	0.3	0.3 -	
100	ç 480	15.6	-17.2	2.5	2.5	2.2	2.1	2.1	2.1	0.7 -	
(m)	440	30.4	26.7	33.8	3.8	0.5	0.6	0.5	0.5	0.4 -	
iteret	390	2.5	0	-0.4	0.9	1.1	2.3	1.6	0.4	0.3 -	
U U	350	0.6	0.3	0.4	1.6	1.6	-8	0.3	1.4	0.4 -	
	300	36	-37.3	-34.5	-43.5	-42.1	-28.2	-3.6	-1.1	-0.3 -	
	260	- 1.7	1.7	-9.1	0	0.1	1	17.3	0.1	0.2 -	
	210	- 2.5	0.8	-2	-4	-4.7	1.1	2.3	2.4	2.3 -	
		0.005	0.01	0.015	0.02	0.025	0.03	0.035	0.04	0.045	
				lnj	jected	Signal	Streng	gth			

CSP - KLIP SNR Comparison, HD 1466

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610	1.9	-3.2	-3.2	-3.2	-3.2	-3	-2.3	-1.6	-1.4 -	-	2
570	1.4	-2.9	-2.9	-2.5	-2.4	-2.3	-2.3	-2.1	-2 -	-	1.5
520	0.7	-2.3	-2.1	-1.7	-1.6	-2.4	-1.7	-1.7	-1.2 -	-	1
3 480	- 0.1	-1.1	-1.4	-1.4	-1.4	-2.5	-2.4	-1.4	-1.4 -	-	0.5
440	- 0.4	-0.5	-1	-1	-0.8	-0.7	-0.6	-0.3	-0.2 -	-	0
390	- 0.5	0.2	0	-0.3	-0.5	-0.3	-0.5	-0.9	-0.7 -		-0.5
350	- 0.2	0	0.2	0.2	0.2	0.3	0	-0.1	-1.1 -		-1
300	- 0.7	0.3	0.3	0.3	-0.1	-0.1	-0.3	-0.3	-0.3 -		-2
260	- 1.6	1.1	0.9	0.7	1	1.2	1.2	1.1	0.8 -		-2.5
210	- 1.5	1.1	1	0.6	0.6	1.5	2.2	1.8	1.3 -		-3
	0.005	0.01	0.015	0.02	0.025	0.03	0.035	0.04	0.045		

Injected Signal Strength

.5

.5

.5

Images (Left: CSP, Right: KLIP)





Conclusions and Future Work

- Common Spatial Pattern Filtering can be used to extract planet signals from direct imaging
- Tentatively, CSP has higher SNR near inner working angle
- Higher rate of false positives

- Matched Filter
- Validate on more star backgrounds
- Develop procedure for SDI inclusion
- Optimally sized regions



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