Astrophysical and Instrumental Noise Sources: Direct Imaging

Laurent Pueyo, Space Telescope Science Institute

Sagan Summer Workshop, 2016

July 21, 2016
Images in multiple bands, Macintosh et al, 2015

How do we make blobs appear? How do we decide a blob might be a planet?
The example of 51 Eri b with the Gemini Planet Imager

**Spectrum**, Macintosh et al, 2015

How do we get a spectrum?
Orbit, mass?, De Rosa et al, 2015

How do we carry out precise astrometric measurements?
This talk

1. High-contrast image formation theory.
2. High-contrast data analysis.
3. Handling astrophysical noise.
Fourier Transforms
THE EFFECTS OF ATMOSPHERIC TURBULENCE IN OPTICAL ASTRONOMY

BY

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Fourier Transforms

Let us denote $O(\alpha)$ the irradiance distribution from the object as a function of the direction $\alpha$ on the sky. $I(\alpha)$ will be the observed irradiance distribution, in the instantaneous image, as a function of the same variable $\alpha$. A long exposure image will be considered as the ensemble average $\langle I(\alpha) \rangle$. Since astronomical objects are entirely incoherent, the relation between $\langle I(\alpha) \rangle$ and $O(\alpha)$ is linear. We shall moreover assume that it is shift invariant, i.e., the telescope is isoplanatic and the average effect of turbulence is the same all over the telescope field of view. In such a case, $\langle I(\alpha) \rangle$ is related to $O(\alpha)$ by a convolution relation

$$\langle I(\alpha) \rangle = O(\alpha) * S(\alpha)$$  \hspace{1cm} (4.1)

the point spread function $\langle S(\alpha) \rangle$ being the average image of a point source.

We shall define the two-dimensional complex Fourier transform $\tilde{I}(\mathcal{f})$ of $I(\alpha)$ as

$$\tilde{I}(\mathcal{f}) = \int d\alpha \cdot I(\alpha) \cdot \exp(-2i\pi \alpha \cdot \mathcal{f})$$  \hspace{1cm} (4.2)

with similar relations for the Fourier transform $\tilde{O}$ and $\tilde{S}$ of $O$ and $S$. In these expressions the spatial frequency vector $\mathcal{f}$ has the dimension of the inverse of the angle $\alpha$ and must therefore be expressed in radian$^{-1}$. With such a definition, (4.1) becomes, in the Fourier space

$$\langle \tilde{I}(\mathcal{f}) \rangle = \tilde{O}(\mathcal{f}) \cdot \langle \tilde{S}(\mathcal{f}) \rangle$$  \hspace{1cm} (4.3)

where $\langle \tilde{S}(\mathcal{f}) \rangle$ is the optical transfer function of the whole system, telescope and atmosphere.
Fourier Transforms

chromatic point source, of wavelength $\lambda$. Again, we shall denote $\Psi_0(x)$ as the complex amplitude at the telescope aperture. The complex amplitude $\mathcal{A}(\alpha)$ diffracted at an angle $\alpha$ in the telescope focal plane is proportional to

$$\mathcal{A}(\alpha) \propto \int dx \cdot \Psi_0(x) P_0(x) \exp (-2i\pi \alpha \cdot x/\lambda) \quad (4.4)$$

where $P_0(x)$ is the transmission function of the telescope aperture. For an ideal diffraction-limited telescope,

$$P_0(x) = \begin{cases} 1 & \text{inside the aperture} \\ 0 & \text{outside the aperture} \end{cases} \quad (4.5)$$

In the case of aberrated optics, wavefront errors are introduced as an argument of the complex transmission $P_0(x)$.

In the following, we shall make extensive use of the non-dimensional reduced variable

$$u = x/\lambda. \quad (4.6)$$

Let us call

$$\Psi(u) = \Psi_0(\lambda u) \quad \text{and} \quad P(u) = P_0(\lambda u). \quad (4.7)$$

With such notation (4.4) becomes

$$\mathcal{A}(\alpha) \propto \mathcal{F}[\Psi(u) \cdot P(u)] \quad (4.8)$$
where $\mathcal{F}$ is the complex Fourier transform defined by (4.2). The point spread function is the irradiance diffracted in the direction $\alpha$

$$S(\alpha) = |A(\alpha)|^2 \propto |\mathcal{F}[\Psi(u)P(u)]|^2.$$  \hspace{1cm} (4.9)

Its Fourier transform is given by the autocorrelation function of $\Psi(u)P(u)$

$$\tilde{S}(\mathfrak{r}) \propto \int du \cdot \Psi(u)\Psi^*(u + \mathfrak{r})P(u)P^*(u + \mathfrak{r}).$$  \hspace{1cm} (4.10)

In the absence of any turbulence, we assume that $\Psi(u) = 1$ (§ 3) so that, normalising $\tilde{S}(\mathfrak{r})$ to unity at the origin,

$$\tilde{S}(\mathfrak{r}) = \mathcal{S}^{-1} \int du \cdot P(u)P^*(u + \mathfrak{r}) = T(\mathfrak{r})$$  \hspace{1cm} (4.11)

where $\mathcal{S}$ is the pupil area (in wavelength squared units). Eq. (4.11) is the classical expression for the optical transfer function $T(\mathfrak{r})$ of a telescope.
Fourier Transforms

In the presence of turbulence (4.11) becomes

\[ \tilde{S}(\chi) = \mathcal{F}^{-1} \int du \cdot \Psi(u)\Psi^*(u + \chi)P(u)P^*(u + \chi) \]  \hspace{1cm} (4.12)

and the optical transfer function for long exposures is

\[ \langle \tilde{S}(\chi) \rangle = \mathcal{F}^{-1} \int du \langle \Psi(u) \cdot \Psi^*(u + \chi) \rangle P(u)P^*(u + \chi). \]  \hspace{1cm} (4.13)

In (4.13) appears the second order moment

\[ B(\chi) = \langle \Psi(u) \cdot \Psi^*(u + \chi) \rangle = B_0(\lambda \chi) \]  \hspace{1cm} (4.14)

the properties of which have been studied in § 3. Since \( B(\chi) \) depends only upon \( \chi \), (4.13) can be written, taking (4.11) into account,

\[ \langle \tilde{S}(\chi) \rangle = B(\chi) \cdot T(\chi) \]  \hspace{1cm} (4.15)

showing the fundamental result that, for long exposures, the optical transfer function of the whole system, telescope and atmosphere, is the product of the transfer function of the telescope with an atmospheric transfer function equal to the coherence function \( B(\chi) \).
Botton Line

- **Main sources of noise** = whatever is at the telescope entrance, e.g. atmospheric turbulence and imperfections on the optics.

- **In direct imaging data** their **Fourier Transform** is the relevant quantity for noise estimation. For long exposures we care about the Fourier Transform of the auto-correlation of the errors at the telescope entrance averaged over time.
Guyon (2005).

**Bottom Line**
- Main sources of noise = whatever is at the telescope entrance, e.g. atmospheric turbulence and imperfections on the optics.
- If we “broadly” know what they look like, we can predict what the images will look like.
Complex amplitude at the entrance of the coronagraph, assuming no time variations:

\[
\psi_0(x) = Beam_{Amplitude}(x) \exp[i Beam_{Delay}(x)]
\]

\[
\psi_0(x) = [1 + \varepsilon_A(x)] \exp[i \varepsilon_{OPD}(x)/\lambda]
\]

\[
\psi_0(x) \sim 1 + \varepsilon_A(x) + i \varepsilon_{OPD}(x)/\lambda \sim \varepsilon_A(x) + i \varepsilon_{OPD}(x)/\lambda
\]
Speckles: symmetries

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Soummer et al. (2008).
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\[
\psi_0(x) \sim \varepsilon \cos\left(\frac{2\pi D}{n} nx + \phi\right) \text{ and } \int d\mu \psi_0(\mu) \psi_0(\mu + f)^* \sim \varepsilon \cos\left(\frac{2\pi}{D} nf + \phi\right)
\]

Pueyo et al. (2009).
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\[ \psi_0(x) \sim i \varepsilon \cos\left(\frac{2\pi}{D} nx + \phi\right) \text{ and } \int d\mathbf{u} \psi_0(\mathbf{u}) \psi_0(\mathbf{u} + \mathbf{f})^* \sim i \varepsilon \cos\left(\frac{2\pi}{D} n\mathbf{f} + \phi\right) \]

Pueyo et al. (2009).
Speckles: symmetries

Complex amplitude at the entrance of the coronagraph, assuming no time variations:

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\psi_0(x) = [1 + \epsilon_A(x)] \exp\left[i \frac{\epsilon_{OPD}(x)}{\lambda}\right] \\
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\]

Pueyo and Norman (2013).
Speckles: Temporal evolution

Hinkley et al. (2007).

Quick derivation of the respective influence of atmospheric and “quasi-static” (e.g. from telescope/instrument optics) speckles.

\[ \psi_0(x) = \left[ \varepsilon_{Atm}(t) + \varepsilon_{Tel}(t) \right] \cos\left( \frac{2\pi}{D} nx + \phi \right) \]

\[ S(f) = \int du \left< \psi_0(u) \psi_0(u+f)^* \right>_{\exp} \]

\[ \sim \left[ \sigma_{Atm}^2 + 2 \left< \varepsilon_{Atm}, \varepsilon_{Tel} \right>_{\exp} + \ldots \right] \]

\[ \ldots + \left< \varepsilon_{Tel}, \varepsilon_{Tel} \right>_{\exp} \cos\left( \frac{2\pi}{D} nf + \phi \right) \]

Rigorous derivation in Perrin et al. (2005).
Speckles: Temporal evolution
Speckles: Temporal evolution

Bailey et al. (2016).
Speckles: Temporal evolution

Bailey et al. (2016).

Key temporal properties of speckles

- The atmosphere creates speckles, but they average out into a broad halo.
- Adaptive Optics performances dictates the shape of this “average halo”.
- The telescope+instrument speckles are pinned to the AO response.
- The telescope+instrument speckles have timescales ranging from exposure time to observing sequence.
Speckles: wavelength dependence
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chromatic point source, of wavelength $\lambda$. Again, we shall denote $\Psi_0(x)$ as the complex amplitude at the telescope aperture. The complex amplitude $\mathcal{A}(\alpha)$ diffracted at an angle $\alpha$ in the telescope focal plane is proportional to

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Key morphological properties of speckles

- Speckles look like planets.
- Speckles are symmetric (except when they are not).
- Speckles stretch with wavelength (except when they are not).
Speckles: wavelength dependence

Krist et al. (2016)

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Soummer et al. (2008)
Speckles: statistics

Soummer et al. (2008)

\( S(r) \sim \mathcal{N}(0, I) \). The instantaneous intensity corresponding to the complex amplitude of equation (12) is simply

\[
I = |S(r) + \tilde{C}(r)|^2
\]

\[
= \left\{ \text{Re}[\tilde{C}(r) + S(r)] \right\}^2 + \left\{ \text{Im}[\tilde{C}(r) + S(r)] \right\}^2.
\]

(15)

where \( \text{Re} \) and \( \text{Im} \) denote the real and imaginary parts. Using the properties of circular Gaussian distributions, \( \text{Re}[\tilde{C}(r) + S(r)] \) and \( \text{Im}[\tilde{C}(r) + S(r)] \) are independent Gaussian random variables of the same variance \( I/2 \). We can rewrite the intensity with real and imaginary terms of variance unity,

\[
I = \frac{I}{2} \left( \left\{ \text{Re}\left[\sqrt{2I_s^{-1}} \tilde{C}(r) + S(r)\right]\right\}^2 + \left\{ \text{Im}\left[\sqrt{2I_s^{-1}} \tilde{C}(r) + S(r)\right]\right\}^2 \right) = \frac{I}{2} \tilde{I},
\]

(16)

where \( \text{Var}[\text{Re}\left(\sqrt{2I_s^{-1}} \tilde{C}(r) + S(r)\right)] = \text{Var}[\text{Im}\left(\sqrt{2I_s^{-1}} \tilde{C}(r) + S(r)\right)] = 1 \).

The random variable \( \tilde{I} \) follows a decentered \( \chi^2 \) with two degrees of freedom, \( \chi^2(m) \), with a decentering parameter \( m = 2I_s^{-1}I \). (Johnson et al. 1995, p. 433). The PDF for \( \tilde{I} \) is therefore

\[
\mathcal{P}(v) = 2^{-1} e^{-v/2} f_1 \left( \frac{1}{4} mv \right), \quad v > 0,
\]

(17)

where \( f_1(z) \) is the regularized confluent hypergeometric function and \( \phi F_1(; q; z) \) is the confluent hypergeometric function defined as

\[
\phi F_1 = \sum_{n=0}^{\infty} \frac{1}{\Gamma(q+n)n!} z^n = \phi F_1(; q; z).
\]

(18)

Finally, the PDF of the intensity \( I \) is \( I/2\tilde{I} \)

\[
p_I(I) = \frac{e^{-I/2\tilde{I}}}{\tilde{I}} F_1 \left( ; 1; \frac{I}{\tilde{I}} \right).
\]

(19)

This expression is equivalent to the “modified Rician distribution” derived by Goodman (1975) and used by Caginal & Canales (1998, 2000) and Canales & Caginal (1999, 2001):

\[
p_I(I) = \frac{1}{I} \exp \left( -\frac{I+I_s}{I_s} \right) I_s \left( \frac{2\sqrt{I/I_s}}{I_s} \right).
\]

(20)

This PDF corresponds to the well-known negative exponential density for a fully developed speckle pattern (e.g., laser speckle pattern; Goodman 2000). Finally, the distribution at photon counting levels can be obtained by performing a Poisson-Mandel transformation of the high-flux PDF in equation (20). An analytical expression of this PDF has been given in Aime & Soummer (2004b).

The mean and variance of the intensity can be obtained by several ways. A first method (Goodman 1975, 2000) is to express the mean intensity \( E(I) \) and the second-order moment of the intensity \( E(I^2) \) as functions of \( C(r) \) and \( S(r) \). The second-order moment for the intensity is the fourth-order moment for the complex amplitude, \( E(I^2) = E((C + S)(C^* + S^*))^2 \) (omitting the variables \( r \) for clarity), which can be simplified using the properties of Gaussian distributions. With \( E(SS^*SS^*) = 2E(SS^*)E(SS^*) = 2I_s^2 \) we obtain \( E(I^2) = I_s^2 + 4I_s I + 2I_s^2 \). A second method is to derive a general analytical expression for the moments of the Rician distribution. This can be obtained either from the definition of the moments of equation (20) (Goodman 1975) or by computing the derivatives of the moment-generating function (Aime & Soummer 2004b). The instantaneous intensity in the focal plane (eq. [15]) can be written as

\[
I = |C(r)|^2 + |S(r)|^2 + 2\text{Re}[C^*(r)S(r)].
\]

(22)

Since \( E(SS^*) = E(S^*)^2 = 0 \) (circular Gaussian distribution), the mean intensity is simply the sum of the deterministic diffraction pattern with a halo produced by the average of the speckles, \( I_s + I_c \) or \( I_s + I_h \), respectively, for direct and coronagraphic images. The variance also finds a simple analytical expression, and we have

\[
E(I) = I_s + I_c,
\]

\[
\sigma_I^2 = I_s^2 + 2I_s I_c.
\]

(23)

The variance associated with photodetection can be added to this expression to obtain the total variance \( \sigma^2 = \sigma_s^2 + \sigma_I^2 \), where \( \sigma_s^2 \) is the variance associated with the Poisson statistics, \( \sigma_s^2 = I_s + I_c \). The total variance is therefore

\[
\sigma^2 = I_s^2 + 2I_s I_c + I_c + I_h.
\]

(24)

In the case of direct images, the term \( I_c \) corresponds to the perfect PSF scaled to the SR. In the case of coronagraphic images, the focal plane intensity is not invariant by translation, and therefore, it is technically not a true PSF. However, we use the...
Speckles: statistics

Soummer et al. (2008)
Speckles: statistics

Courtesy of A. Rajan and the GPI team.
Key questions

Key statistical properties of speckles

- Speckles follow a Modified Rician distribution (long positive tail).
- Second order moment depends on angular separation and on how well the coronagraph works.
Airing of grievances

Key annoying properties of speckles

- Speckles look like planets.
- Speckles follow a Modified Rician distribution (long positive tail).
- Second order moment depends on angular separation, on how well the coronagraph works and how well the atmosphere averages out.
- The telescope+instrument speckles have timescales ranging from exposure time to length of an observing sequence.

The most successful method to analyze direct imaging data so far has been to build an empirical model of the noise based on the data itself.
The problem(s)

Assume you have an image in which you are looking for a planet.

\[ T(n) = I_{\psi_0}(n) + \epsilon A(n). \]

We call \( \psi \) the random state of the telescope+instrument at the exposure.

The problem we want to solve is to figure out what are the relative contributions of the light diffracted within the instrument and of an hypothetical astrophysical signal.

Solutions

- We can have a really good model of our instrument.
- We “construct” a really good model of our instrument based on its data history (science frames+telemetry).
- We get more realizations of \( I_{\psi} \) for which we are sure that there is no astrophysical signal. We subtract them from \( T \).
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Observing strategies

How to get more realizations of the instrument response?

- Take images of other sources.

$$\varepsilon A(n) = I_{\psi_0}(n) - I_{\psi_1}(n)$$

What to watch for:

- The telescope + instrument must be very stable.
- The alignment of the images needs to be very precise (the star needs to be on the same fraction of a pixel).
Observing strategies

How to get more realizations of the instrument response?

- Take images of other sources.

$$\varepsilon A(n) = l_{\psi_0}(n) - l_{\psi_1}(n)$$

What to watch for:

- The telescope + instrument must be very stable.
- The alignment of the images needs to be very precise (the star needs to be on the same fraction of a pixel).
Observing strategies

How to get more realizations of the instrument response?

- Take images of other sources.
- Take images at other wavelengths/telescope orientations.

\[ R(n) = I_{\psi_1}(n) + \epsilon A(n - \delta n_{1r,\theta}) \text{ or } R(n) = I_{\psi_1}(n - \delta n_{1r,\theta}) + \epsilon A(n) \]

Credit: P. Ingraham and the GPI team
Solving the least squares problem:

$$\min_{\{c_k\}} \left\{ \sum_n \left( T(n) - \sum_{k=1}^{K} c_k R_k(n) \right)^2 \right\}.$$ 

Equivalent to:

$$E[RR] C = T$$

where $E[RR]$ is the correlation matrix of the ensemble of references over the zone of the image we chose.

Several routes to invert this:

- Tweak set up of the inverse problem (geometry, selection of references)
- Regularize of the inverse problem (SVD truncation, PCA)
Solving the least squares problem:

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\min_{\{c_k\}} \left\{ \sum_n \left( T(n) - \sum_{k=1}^K c_k R_k(n) \right)^2 \right\}.
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LOCI - KLIP

Solving the least squares problem:

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Equivalent to:

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This is where the magic happens

Marois et al. (2008), Marois et al. (2010)
This is where the magic happens

Marois et al. (2008), Marois et al. (2010)
This is where the magic happens

Oppenheimer et al. (2013), Pueyo et al. (2015)
This is where the magic happens

Soummer et al. (2011)
This is where the magic happens

Rameau et al. (2012)
False positives and false negatives

The initial speckles follow Rice statistics, (hopefully) the steps above make them “more” Gaussian, Marois et al. (2007).
False positives and false negatives

When working at small separations a penalty term needs to be taken into account to include uncertainties associated with small number statistics when estimating the empirical variant of the noise, Mawet et al. (2014).
False positives and false negatives

In the case of a detection we care about the False Positive Fraction. In the case of upper limits we care about the True Positive Fraction, Wahhaj et al. (2015)

\[
\text{FPF} = \frac{FP}{FP + TN} \\
\text{FDR} = \frac{FP}{FP + TP} \\
\text{TDR} = \frac{TP}{FP + TP} \\
\text{TPF} = \frac{TP}{FN + TP}
\]
An “observer” convert pixel maps into one scalar number that measures how the confidence in the detection of signal. The Receiver Operating Characteristic of a given observer illustrates how the FPF and TPF varies when the decision making threshold changes. Caucci et al. (2012).

**Decision making process**
- Pick an algorithm to subtract noise and observer.
- Based on the noise properties and the observer calculate ROC.
- Figure out optimal threshold on the ROC to classify date under the assumption of a given utility function.

A utility function assigns costs:
- False Positives: cost is the non detections of a planet that is actually there.
- False Negative: cost is using telescope resources to follow up a “speckle” while those could be allocated to the detection a planet that is actually there, around another star.
Problem....PSF subtraction algorithms also subtract the signal
Problem...PSF subtraction algorithms also subtract the signal.

The least squares speckles fitting in the presence of signal can be written as:

$$\min_{\{c_k\}} \left\{ \sum_n \left( [I_{\psi_0}(n) + A_0(n)] - \sum_{k=1}^{K} (c_k + \delta c_k)[I_{\psi_k}(n) + A_k(n)] \right)^2 \right\}.$$
Problem... PSF subtraction algorithms also subtract the signal.

Solution is to inject a negative model of the signal in the entire observing sequence and minimize the residuals over a range of hypothetical astrophysical observables. This can be done in conjunction with any of the algorithms described before. Marois et al. (2010), Lagrange et al. (2012).
Solution is to inject a negative model of the signal in the entire observing sequence and minimize the residuals over a range of hypothetical astrophysical observables. Example of a grid search for astrometry and photometry, Morzinski et al. (2015).
Problem....PSF subtraction algorithms also subtract the signal

Solution is to inject a negative model of the signal in the entire observing sequence and minimize the residuals over a range of hypothetical astrophysical observables. Example of an MCMC for astrometry and photometry, Bottom et al. (2014).
Problem: PSF subtraction algorithms also subtract the signal

Solution is to inject a negative model of the signal in the entire observing sequence and minimize the residuals over a range of hypothetical astrophysical observables.

Main drawbacks

- The speckle subtraction algorithm has to be used each time around (involves a matrix inversion).
- There is no guarantee that the cost-function minimized/likelihood explored does not feature local minima. One might get stuck in them.
- In general these are not limiting factors in "small dimensional configurations" (astrometry and photometry = 3 dimensions).
- This becomes a severe limiting factor when trying to get spectrum (astrometry and spectrum = 39 dimensions with GPI).
Fortunately, we can actually predict what will happen.

There is a way to write the influence of the astrophysical signal as:

\[ \text{PCA}(\text{Speckles} + \text{Signal}) = \text{PCA}(\text{Speckles}) + \text{Signal} \delta \text{PCA}(\text{Speckles}) \]

...and this applies to any algorithm relying on covariances. Pueyo (2016).

Aggressive reduction: \( N_r = 5, \ N_\phi = 4, \ N_{\text{Corr}} = 50, \ K_{\text{Klip}} = 50, \ N_\delta = 0.6. \)
Fortunately, we can actually predict what will happen

There is a way to write the influence of the astrophysical signal as:

$$PCA(Speckles + Signal) = PCA(Speckles) + Signal \delta PCA(Speckles)$$

...and this applies to any algorithm relying on covariances. Pueyo (2016).

Non aggressive reduction: $N_r = 5$, $N_\phi = 4$, $N_{Corr} = 30$, $K_{Klip} = 30$, $N_\delta = 0.8$. 

Horizontal cut
Counts
Counts
Vertical cut
Injected
After KLIP
Linear model
Point Source as bright as speckles
Fortunately, we can actually predict what will happen

There is a way to write the influence of the astrophysical signal as:

\[
PCA(Speckles + Signal) = PCA(Speckles) + Signal \delta PCA(Speckles)
\]

...and this applies to any algorithm relying on covariances. Pueyo (2016).

Non aggressive reduction: \(N_r = 5, N_\phi = 4, N_{\text{Corr}} = 30, K_{\text{Klip}} = 30, N_\delta = 1\).
Fortunately, we can actually predict what will happen

There is a way to write the influence of the astrophysical signal as:

\[
\text{PCA}(\text{Speckles} + \text{Signal}) = \text{PCA}(\text{Speckles}) + \text{Signal} \, \delta \text{PCA}(\text{Speckles})
\]

...and this applies to any algorithm relying on covariances. Pueyo (2016).

- Aggressive reduction: \( N_r = 5, \, N_\phi = 4, \, N_{\text{Corr}} = 50, \, K_{\text{Klip}} = 50, \, N_\delta = 0.6. \)
Fortunately, we can actually predict what will happen

There is a way to write the influence of the astrophysical signal as:

\[ \text{PCA}(\text{Speckles} + \text{Signal}) = \text{PCA}(\text{Speckles}) + \text{Signal} \delta \text{PCA}(\text{Speckles}) \]

...and this applies to any algorithm relying on covariances. Pueyo (2016).

---

The linear model works:

- If the astrophysical source is faint when compared to the speckles.
- If the astrophysical source as bright as the speckles/brighter, and the algorithm parameters are chosen accordingly (not too aggressive).
\[ Y_k(x) = Z_k(x) + \varepsilon \Delta Z_k(x) . \] We can rank them in order of \[ \|\varepsilon \Delta Z_k(x)/Z_k(x)\| . \]

**Three main terms:**

- **over-subtraction**: unperturbed Principal Components \( Z_k(x) \). Scales as \( \|Z_k(x)\| = 1 \).
- **direct self-subtraction**: presence of an astrophysical source at various parallactic angles and wavelengths in the observing sequence multiplied by LOCI coefficient. Scales as \( \varepsilon / \sqrt{\Lambda_k} \).
- **indirect self-subtraction**: perturbation in the LOCI coefficient. Scales as \( \varepsilon / \Theta_k \).

As \( K_{\text{Klip}} \) (e.g. \( \Lambda_k \) decreases) then self-subtraction becomes more and more dominant... estimation of astrophysical observables becomes increasingly complicated.
Application to spectral extraction

Injected vs extracted spectrum

Injected spectrum

Extracted spectrum as a function of PCA order
Application to spectral extraction

Injected vs extracted spectrum

Injected spectrum

Extracted spectrum as a function of PCA order
Application to spectral extraction

Injected vs extracted spectrum

- Flux (arbitrary units)
- Spectral Channel

Non detection = upper limit
Level of noise
Application to spectral extraction

Injected vs extracted spectrum

-0.0020
-0.0015
-0.0010
-0.0005
0.0000
0.0005
0.0010
Spectral Channel
Flux (arbitrary units)

Injected spectrum

Extracted spectrum as a function of PCA order
Application to spectral extraction

Injected vs extracted spectrum

Injected spectrum

Extracted spectrum as a function of PCA order
Application: YJHK Spectrum of β Pic b

Multi-band spectrum of Beta Pic b using latest calibration methods

"Best fit" Spex BD: 2MASS J05361998-192039

low-gravity and young (Faherty et al. 2013)

Application to astrometry

Wang et al. (2016).
Application to astrometry

Wang et al. (2016).

Figure 2. Posterior distribution of the four parameters in the MCMC fit for the astrometry for the 2014 November 18 epoch. The vertical dashed lines in the marginalized posterior distribution plots indicate the 16th, 50th, and 84th percentile values.

Overall though, this GPI Pic b data is an excellent demonstration for Bayesian KLIP-FM Astrometry as the planet is bright enough that the extended PSF features, such as the negative self-subtraction lobes, are clearly seen and provide significant information to constrain the position of the planet. For fainter planets, the extended features are harder to distinguish from the noise.

As one of the main advantages of BKA over techniques that do not forward model the PSF is being able to forward model the extended self-subtraction lobes, the astrometric improvement would not be as large for lower signal-to-noise ratio planets. There still should be some improvement though due to accurately modeling the over-subtraction on the core of the PSF and small contributions from the extended features even if they are hard to distinguish from noise. Regardless, in addition to the improved precision, BKA should also more accurately estimate the uncertainties as it fits for the correlation scale of the noise at the location of the planet.

Table 2

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<th>Dataset</th>
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<th>y (mas)</th>
<th>Uncertainty (mas)</th>
<th>x (mas)</th>
<th>y (mas)</th>
<th>Uncertainty (mas)</th>
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Table 2 continued
Application to astrometry

Wang et al. (2016).

Wang et al.
Application to astrometry

Wang et al. (2016).

Validation through Orbit Fitting
Wang et al. Submitted.
Application to planet detection

**Forward Modeling for the detection problem**

- Forward Modeling does not change the False Positive Fraction (does not change the post KLIP speckles statistics).
- Forward Modeling changes the True Positive Fraction (does change the post KLIP astrophysical flux).
Application to planet detection

Forward Modeling for the detection problem

- Forward Modeling does not change the False Positive Fraction (= does not change the post KLIP speckles statistics).
- Forward Modeling changes the True Positive Fraction (= does change the post KLIP astrophysical flux).

Receiver Operating Characteristic for point sources as bright as speckles
Application to planet detection

Ruffio et al., in prep.

- **Classic KLIP** vs. **FMMF**
- **Fake Planets**

**Data Analysis**

- Noise (N)
- Template (T)
- Observation (Y)
- Noise injected in GPIES data
- FMMF improves the SNR
- Fake Planets

**Key questions**

- Method: Matched Filter
- Improving Exoplanet Sensitivity with Direct Imaging
  - The Forward Model Captures PSF Biases
- Noise (N)
- Template (T)
- Observation (Y)
- ROC for Different Metrics
- FMMF improves the SNR
Application to planet detection

Ruffio et al., in prep.

FMMF improves the SNR

![FMMF improvement graph](image_url)
Application to planet detection

Ruffio et al., in prep.

**ROC for Different Metrics**

- **FMMF** improves the SNR by 50%.
- **Fake Planets** injected in GPIES data.
Application to planet detection

Ruffio et al., in prep.

The Receiver Operating Characteristic (ROC) indicates the cost of a true detection in term of false positives. It is the right tool to compare detection metrics. Contrast curves from different metrics should be drawn at the same false positive rate, which is not necessarily $5\sigma$. 
Macintosh et al. (2015)

How are survey results presented

- Pick the “right” contrast curve for each star. Delta mag vs separation.
- Convert into Mass vs SMA using your favorite model for mass-luminosity and Monte Carlo simulations to explore all possible orbits.
- Convert into Mass vs SMA using your favorite model for mass-luminosity and analytical propagation of priors.
- Sum over all stars in survey.
The Receiver Operating Characteristic (ROC) indicates the cost of a true detection in term of false positives. It is the right tool to compare detection metrics. Contrast curves from different metrics should be drawn at the same false positive rate, which is not necessarily $5\sigma$.

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- Sum over all stars in survey.
Contrast curves and completeness

Wahhaj et al. (2013)

How are survey results presented

- Pick the “right” contrast curve for each star. Delta mag vs separation.
- Convert into Mass vs SMA using your favorite model for mass-luminosity and Monte Carlo simulations to explore all possible orbits.
- Convert into Mass vs SMA using your favorite model for mass-luminosity and analytical propagation of priors.
- Sum over all stars in survey.
Contrast curves and completeness

Savransky et al. (2010)

How are survey results presented

- Pick the “right” contrast curve for each star. Delta mag vs separation.
- Convert into Mass vs SMA using your favorite model for mass-luminosity and Monte Carlo simulations to explore all possible orbits.
- Convert into Mass vs SMA using your favorite model for mass-luminosity and analytical propagation of priors.
- Sum over all stars in survey.
Contrast curves and completeness

Brandt et al. (2014)

How are survey results presented

- Pick the “right” contrast curve for each star. Delta mag vs separation.
- Convert into Mass vs SMA using your favorite model for mass-luminosity and Monte Carlo simulations to explore all possible orbits.
- Convert into Mass vs SMA using your favorite model for mass-luminosity and analytical propagation of priors.
- Sum over all stars in survey.
Other methods

Moving forward with data analysis

By and large most of the community is using “blind” Principal Component Analysis to analyze high-contrast imaging data. This is an ancient method! There is room to do better:

- Use correlation between telemetry and images (Vogt et al., 2010).
- Use the images (and maybe telemetry) a physical model of the complex field at the telescope entrance (Ygouf et al., 2012).
- Give up on the L2 norm (L1 norm?).
- Use only positive modes and positive coefficients (Non Negative Matrix Factorization).
- “Track” the motion of the planet in the data (low rank sparse decomposition, LLSG, Gomez et al., 2016).
Astrophysical false positives
Common proper motion for physical association

Combine proper motion and parallactic motion to establish physical association. Rameau et al. (2013), Mawet et al. (2012)
Common proper motion for physical association

Combine proper motion and parallactic motion to establish physical association. Rameau et al. (2013), Mawet et al. (2012)

Speeding the process up

- This used to be a waiting game: proper and parallactic motion need to be larger than uncertainty in astrometry.
- Smaller error bars for astrometry do certainly help.
- How to use MCMC to speed things up?
Monitoring the orbital motion of exoplanets, through direct imaging (e.g., Chauvin et al. 2012; Kalas et al. 2015). While the orbital parameters before a significant portion of the orbit systems can lead to preliminary constraints on their orbital periods are typically decades or longer for directly imaged planets, accurate astrometric monitoring of these planetary companions dynamically interact with circumstellar material (e.g., Millar-Blanchaer et al. 2015). While the primary companions dynamically interact with circumstellar planar stability arguments (e.g., Correia et al. 2005). Orbits of exoplanets can constrain their masses and densities (e.g., Charbonneau et al. 2000) and lead either to transit measurements (e.g., Cumming et al. 2008; Bonnefoy et al. 2014; Nielsen et al. 2014), or in the case of infrared excess indicative of a circumstellar debris disk (Patel et al. 2014; Riviere-Marichalar et al. 2015), can provide a wealth of information about their outer disc. The debris disk has yet to be spatially resolved, so its geometry is unconstrained. At a projected separation of 13 AU (Montet et al. 2014) reported the discovery of a low-mass (2–10 M_Jup) candidate was identified, and subsequent observations closer brown dwarf interlopers with non-zero proper motion. A statistical argument could not be excluded. A statistical argument for the discovery of additional planets in the system (e.g., Howard et al. 2012; Marcy et al. 2014; Moutou et al. 2015), or to the exclusion of additional astrometry of 51 Eri b from 2014 December to 2015 January 29, where 51 Eri b was not recovered due to a probability of 2 \times 10^{-6}.

H -band filters. In addition to these successful observations, 51 Eri was initially observed with GPI at Gemini South in 2013 December 18 UT (GS-2014B-Q-500). A faint companion was acquired before transit to maximize field rotation as a part of the GPI Exoplanet Survey (GPIES) on 2014 January 29, where 51 Eri b was not recovered due to a probability of 2 \times 10^{-6}.

GPI H
GPI J
Keck L'

Likely Orbits (68% 95% 99.7%)
Background Object

Common proper motion for physical association

De Rosa et al. (2015)
Common proper motion for physical association

De Rosa et al. (2015)

Speeding the process up

- This used to be a waiting game: proper and parallactic motion need to be larger than uncertainty in astrometry.
- Smaller error bars for astrometry do certainly help.
- The “astrophysical noise” hypothesis can also be fitted for.
FIG. 2.— Color-magnitude diagram of field (black diamonds) and young (purple open circles) low-mass stars and brown dwarfs compared with the bona fide or high confidence brown dwarf members of AB Doradus (red stars). Field dwarfs with spectral types in the T5–T6 range are circled in green for comparison with SDSS J1110+0116. Young directly imaged planets, substellar companions and isolated brown dwarfs are displayed as blue right-pointing triangles for comparison. The NIR colors of SDSS J1110+0116 are unusually red compared with field dwarfs of similar spectral types, despite its normal absolute J-band magnitude. J and K magnitudes are displayed in the Mauna Kea Observatory (MKO) system. (A color version of this figure is available in the online journal.)

These objects fall on the right of the field sequence, an effect that is also observed for earlier-type young brown dwarfs and planetary-mass companions (e.g., Metchev & Hillenbrand 2006; Kirkpatrick et al. 2008; Burgasser et al. 2010; Barman et al. 2011; Liu et al. 2013a; Faherty et al. 2013). We note that SDSS J1110+0116 has absolute magnitudes similar to field T5–T6 dwarfs in the 2MASS J, H, Ks and WISE W1 and W2 bands (Dupuy & Liu 2012). This may reflect a balance between a large radius and enhanced dust opacity in its high atmosphere. A compilation of the properties of SDSS J1110+0116 are listed in Table 1.

4.4. The Search for a Co-Moving Companion

We performed a search for a co-moving companion to SDSS J1110+0116 using all 335 2MASS entries within a conservatively large radius of 150, which corresponds to \( \sim 17,000 \) AU at the distance of SDSS J1110+0116. We cross-matched every 2MASS source with the AllWISE catalog using the method described in Paper V. The proper motions that we derived for this set of objects have a median precision of \( \sim 20 \) masyr for both \( \mu \cos \alpha \) and \( \mu \sin \alpha \). We find no object matching the proper motion of SDSS J1110+0116 within 150 and \( < 240 \) masyr. We can thus reject the possibility of a common proper motion companion that would be bright enough to be detected in the 2MASS and AllWISE catalogs. The faintest of these 335 objects has \( J = 17.3 \) and \( W_1 = 17.1 \), and the completeness limits of 2MASS and AllWISE are \( J = 15.8 \) (Skrutskie et al. 2006) and \( W_1 = 17.1 \), respectively.

5. CONCLUSION

Using existing previously reported astrometry and a new radial velocity measurement coupled with low-gravity features in its atmosphere, we have determined that SDSS J1110+0116 is a T5.5 bona fide member of AB Doradus, with an estimated mass of \( \sim 10^{-12} \) M\(_{\text{Jup}}\). This is one of the coldest member of any young moving group identified so far and its relatively high brightness will make it useful to better understand how age and surface gravity shape the atmospheres of low-mass brown dwarfs and planets, influence evolution, and guide future searches for planetary-mass members of young moving groups. This new object falls into a region of the mass/age

1 See http://wise2.ipac.caltech.edu/docs/release/allwise/expsup/sec2_4a.html
The fact that spectrum of the point source looks like a cool T dwarf enabled to calculate the contamination probability only using one epoch and a non detection in 2003.

Macintosh et al. (2015)
Carson et al. (2009)

The mass of Kappa Andromeda
Spiegel and Burrows (2010)

We need the age of the system to tie the luminosity of the companion to its mass using evolutionary tracks.
Age of stars: an oral story

Carson et al. (2009)

The mass of Kappa Andromeda

- Discovery paper, young (∼ 50 Myrs) moving group, mass ∼ 12 $M_{\text{Jup}}$. 
Age of stars: an oral story

Hinkley et al. (2013)

The mass of Kappa Andromeda

- Discovery paper, young ($\sim 50$ Myrs) moving group, mass $\sim 12 \ M_{Jup}$.
- Second look: moving group membership not so convincing, star too bright to be young. Revised age $\sim 200$ Myrs, mass $\sim 30 \ M_{Jup}$. 
Age of stars: an oral story

Hinkley et al. (2013)

The mass of Kappa Andromeda

- Discovery paper, young (~ 50 Myrs) moving group, mass ~ 12 \( M_{Jup} \).
- Second look: moving group membership not so convincing, star too bright to be young. Revised age ~ 200 Myrs, mass ~ 30 \( M_{Jup} \).
Age of stars: an oral story

Hinkley et al. (2013)

The mass of Kappa Andromeda

- Discovery paper, young (∼50 Myrs) moving group, mass ∼ 12 \( M_{\text{Jup}} \).
- Second look: moving group membership not so convincing, star too bright to be young. Revised age ∼ 200 Myrs, mass ∼ 30 \( M_{\text{Jup}} \).
Age of stars: an oral story

Jones et al. (2013)

The mass of Kappa Andromeda

- Discovery paper, young (∼ 50 Myrs) moving group, mass ∼ 12 \( M_{\text{Jup}} \).
- Second look: moving group membership not so convincing, star too bright to be young. Revised age ∼ 200 Myrs, mass ∼ 30 \( M_{\text{Jup}} \).
- Third look: it turns out that Kappa And is a pole on fast rotator, which explains why it is over luminous, back to ∼ 50 Myrs, ∼ 12 \( M_{\text{Jup}} \) after all!
Age of stars with bayesian inference


Fig. 3.— Posterior age probability distributions for four Hipparcos stars, each with three metallicity priors: [Fe/H] = 0 ± 0.05 (red histograms), [Fe/H] = 0 ± 0.03 (green histograms), and [Fe/H] = 0 ± 0.09 (blue histograms). HIP 115738: [Fe/H] = 0 ± 0.02 (Barenfeld et al. 2013) and [Fe/H] = 0 ± 0.09 (man et al. 2005; Ortega et al. 2007; Barenfeld et al. 2013). It is also the founding member of the AB Doradus moving group (Zuckerman et al. 2011; Malo et al. 2013; Mamajek & RVn type are chemically peculiar variable stars of Tau Scorpii, while HIP 11680 is a proposed member of the Columba moving group (Zuckerman et al. 2010). The lower limit on the star's age is determined to be 20–25 Myr using the lithium depletion criterion which we ignore. While HIP 115738's variability does, in principle, permit a measurement of its rotational period, unfortunately, stellar rotation periods among variability surveys, ranging from 2 hours (Rimoldini et al. 2012) to 1.4 days (Wraight et al. 2013) and a high-probability member of the AB Doradus moving group (Bell 2014). HIP 115738's variability does, in principle, permit a measurement of the stellar rotation period. Unfortunately, an undisputed measurement of the stellar rotation period would enable us to directly determine its rotational period among variability surveys, ranging from 2 hours to 1.4 days.
Age of stars with bayesian inference

Age of stars with Bayesian inference


Baysian moving group membership. Gagne et al. (2015)
Age of stars with bayesian inference


Baysian moving group membership. Gagne et al. (2015)
Know your noise!

- Methods to mitigate astrophysical noise are somewhat more “modern” than for instrument noise.
- This is because we know more about the universe than about speckles.
- There is a lot of room for growth in the data analysis domain.

Key things to watch out for the future

- GPI and SPHERE (as instruments) are just starting. They are beautiful planet characterization machines.
- Solve the million dollar problem: reconcile RV and direct imaging Jupiter analog occurrence rates? Do we need deeper contrast? Do we need better angular resolution (… and wait for ELTs)?
- The possibility of obtaining short exposures times might completely change this story.
- JWST data might completely challenge the way we think about the instrument noise.
- Properly handling astrophysical noise will be critical for WFIRST.
Thank you