Direct Imaging of Exoplanets Without Background Subtraction: Implications for ELTs

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ABSTRACT
The ultra-high contrast capability required to form images of other solar systems is arguably the highest-profile challenge in astronomy today. The current high-contrast imaging efforts all require background subtraction to separate the planetary image from the image of the host star. Background estimation is difficult due to the presence of non-common path aberrations (NCPAs) that change with time. The only major source of information that is not being utilized by current efforts is the random encoding of the planetary image and the NCPAs by the atmosphere on millisecond time-scales. Here, a method that utilizes this information in order to avoid background subtraction altogether is proposed. This new paradigm will allow simultaneous estimation of the time-dependent NCPAs and the planetary image via rigorous statistical inference procedures. These procedures are fully compatible with other information sources, such as diurnal field rotation and spectral diversity. Given the open-ended nature of the background subtraction issues, the ideas explained herein may well the key to imaging habitable planets with Extremely Large Telescopes (ELTs). Fully exploiting the information content of millisecond exposures will require significant design modifications of the ELT wavefront sensors and science camera systems, if ultra-high contrast imaging is to be priority.

Keywords: exoplanet, adaptive optics, short-exposure imaging, image processing

1. INTRODUCTION
The coming decades will see the construction and operation of a new class of ground-based telescopes with mirrors diameters of 30 m or more. Such an instrument is called an Extremely Large Telescope (ELT), and one of the top science priorities is direct imaging of exoplanets, protoplanetary disks and exo-solar systems. ELTs should allow us to see habitable Earth-like planets via direct imaging, but imperfect knowledge of the telescope’s optical aberrations is the major impediment, as will be discussed below. This type of imaging falls into the category of high-contrast astronomy because the surrounding material is much fainter than the host star, requiring a dynamic range (or “contrast ratio”) of $10^{-9}$ or smaller. This paper suggests that astronomical community should consider the dawn of the ELT era as an opportunity to examine the many ways in which millisecond exposures, which freeze the atmospheric turbulence, are likely to enable new observational capabilities.

The most promising method for achieving high-contrast imaging and spectroscopy combines high-order adaptive optics (AO) with a stellar coronagraph. A stellar coronagraph is a telescopic imaging system designed to block the light from a star on the optical axis while only having minimal effect on the portion of the image surrounding the star. Above the atmosphere, where the star presents the telescope with a flat wavefront, even a relatively simple coronagraph, such as the one on the Advanced Camera for Surveys on the Hubble Space Telescope, can reject the starlight with an efficiency of about

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Figure 1. Example of speckles in an observation of Vega with AO and a coronagraph made by the AEOS telescope in the H-band. The speckle pattern limiting the contrast is clearly evident. Left: A single 8 s exposure, exhibiting quasi-static speckles with lifetimes of a few seconds or greater. Right: A 38 minute exposure showing the quasi-static speckles with lifetime of about 10 minutes or greater. From [3].

However, on the ground, the AO system does an imperfect job of correcting for the atmospheric distortion, leading to far lower rejection ratios, even allowing the majority of the starlight to pass at times when the Strehl ratio is low.[4] Typically, the AO system operates at visible wavelengths, while the science camera in the coronagraph captures images in the near-infrared (IR) at wavelengths of about 1.2 µm or longer. Observing in the near-IR improves the needed contrast ratios and is required for spectroscopy of key molecules such as water and methane. The residual wavefront from the AO system, called the “AO residual,” creates speckles in the image plane that scintillate at millisecond timescales. If the post-AO imaging system were free of diffraction effects and optical aberrations, the amplitude of the speckle oscillations would be a smoothly decreasing function of distance from the center (until the distance corresponding to maximum spatial frequency of the AO correction is reached). In this circumstance, a long-exposure image would have a smooth halo coming from a time-average of the speckles, and subtracting it from a science image to reveal the planetary emission would be a relatively straightforward matter. The most common term for any post-AO aberration (i.e., an aberration that is not sensed by the AO system) is “non-common path aberration” (NCPA). Diffraction rings (or the equivalent, depending on the pupil geometry) and NCPAs interact with the AO residual, creating enhanced speckle amplitudes where the diffracted field is large. This effect has been dubbed “pinned speckle.”[5] Thus, in a real optical system, the speckle amplitude can have a complicated structure, and to the extent that the NCPAs are unknown, the resulting long-exposure background is difficult to subtract. Due to a variety of mechanical stresses on the telescope caused by, for example, winds and temperature gradients, the aberrations are never precisely known and vary temporally over a wide range of time-scales, ranging from high-frequency vibrations to hours. The resulting speckles have been given the name “quasi-static speckles” due to their temporal variability, and several authors have shown that they are the major limitation in high-contrast imaging.[6, 7]

Fig. 1 shows a typical example of the swarm of quasi-static speckles that limit high-contrast imaging.[8] The image shown here is of the star Vega in the H-band and was taken with the 3.6 m AEOS telescope with the AO system and a coronagraph. The left image is a single 8 s exposure. As the speckles that are purely atmospheric (meaning not pinned in the sense described above) average to smooth halo over time-scales much smaller than a second, this image exhibits quasi-static speckles with lifetimes on the order of a few seconds or longer. The image on the right has a total exposure time of almost 40 minutes, and the quasi-static speckles seen here have lifetimes on the order of 10 minutes or greater. Observing modes with contemporary high-contrast imaging systems, such as Project 1640,[8] the Gemini Planet Imager and SPHERE,[9, 10] involve exposure times ranging from several to tens of minutes.

*The Strehl ratio is usually defined as the ratio of peak intensity in the image plane divided by the peak intensity that would be seen if the incoming wavefront were perfectly flat.
utes. In such observations, the quasi-static speckles appear as bright points since their time-averaged intensities are enhanced compared to the smooth background. However, at millisecond-time scales, one sees a fast modulation in their intensities as they interfere coherently with atmospheric speckles, providing much information about the NCPAs.

2. CURRENT METHODOLOGIES AND LIMITATIONS

As the speckle overwhelms the faint planetary emission, dominating the photon noise by orders of magnitude, post-processing of the images is necessary for ground-based high-contrast science, even with coronagraphic optics. Since quasi-static speckles can be present over long periods of time (perhaps hours), long integration times do not significantly improve the achievable contrast. The most important post-processing techniques to date are spectral deconvolution (SD) and angular differential imaging (ADI). ADI and SD are used to estimate the stellar point spread function (PSF), which includes the effects of quasi-static speckles. In theory, the PSF can be subtracted from a target image to reveal the non-stellar emission. SD takes advantage of the fact that the PSF scales with wavelength ($\lambda$), so observations at two or more wavelengths allow for some speckle suppression, and is particularly effective when a strong spectral feature (e.g., the methane band) makes the planet almost disappear at some wavelengths. However, SD is particularly unsuited to optical path errors whose linear sizes are independent of $\lambda$, because they lead to phase errors that scale as $1/\lambda$. Closely related to SD is chromatic differential imaging (CDI), which takes advantage of the fact that the PSF stretches with wavelength while the location of the planet does not change with wavelength. CDI is entirely unsuited to extended targets such as protoplanetary disks (due to self-subtraction) and is also plagued by the highly correlated nature of the polychromatic PSFs close to a star (due to the small changes with wavelength). ADI takes advantage of the diurnal field rotation that occurs over the course of the night when the instrument rotator is turned off (Cassegrain focus) or adjusted to maintain instrument alignment (Nasmyth focus), so that the planet appears to rotate relative to the star and the PSF. Thus, to the extent that aberrations do not evolve as the image rotates around the pointing center, correction can be achieved. ADI is ineffective for star-planet separations close to $\lambda/D$ (where $D$ is the telescope diameter), because the planet must travel a linear distance of several resolution elements within the observing period. ADI has a host of biases creating difficulties for astrometry and photometry. These are caused by a number of effects, such as the fact that the apparent planetary rotation rate around the star is time-dependent (due to the diurnal rotation, not its orbit), being fastest near the transit, where the planet and PSF are smeared during a typical exposure period. Far from the transit, the rotation is too slow to be useful.

Currently, CDI and ADI are implemented within the mathematical framework of locally optimized combination of images (LOCI). LOCI algorithms combine a sequence of images taken at different wavelengths and/or diurnal rotation angles to create the best guess for the PSF image, which can be subtracted from the target image to remove the stellar component. LOCI can be generalized to include polarization differential imaging, non-simultaneous observations of “naked” stars, and simultaneous
observations of off-axis stars to help determine the PSF, however, ADI is generally the most informative of these and is the most widely used. Finding a good image to subtract is a challenge due to the temporal variability of the NCPAs and other effects. In LOCI, one starts with a set of $N$ reference images $\{R_n\}$. When using ADI, these images correspond to different diurnal rotation angles. One subtracts a linear combination of them, $\sum_n c_n R_n$, from the target image $T$ to get the final science image. The “local” nature of LOCI comes from the fact that the coefficients $\{c_n\}$ are chosen independently for each of a number of subregions within the target image. In LOCI/ADI, typically the regions correspond to angular annuli.$^{13,18}$ In the original conception,$^9$ chose the $\{c_n\}$ to minimize $||T - \sum_n c_n R_n||^2$ in each subregion. A more sophisticated variant of LOCI, called KLIP, creates an orthonormal basis from the reference images $\{R_n\}$ via Karhunen-Loève (a.k.a. principle components) transformation.$^{20}$

The various subtraction procedures are problematic due to the very nature of the ADI data (similar considerations apply to CDI as well). The reference set $\{R_n\}$ cannot incorporate images that are taken too close in time to the target because the planet will not have rotated far enough and its light will be self-subtracted. On the other hand, if the reference images are too distant in time, the PSF will have evolved significantly. Thus, there is an optimal time difference, however this optimal time difference depends on the distance between the planet and the star, resulting in saw-tooth like wave (as a function of distance from the star) in the LOCI throughput, which causes leading and/or trailing shadows in the final image, as shown in Fig. 2. This shadowing effect not only causes underestimation of the planetary brightness, but it can bias the astrometry as well.$^{13,18}$ The LOCI processed images also suffer from non-uniform throughput due to the fact that the minimization $||T - \sum_n c_n R_n||^2$ (which implies correlating the target image $T$ with the $\{R_n\}$) will have over-aggressive subtraction where the PSF is brighter.$^{13,18}$ Furthermore, there are a number of issues related to errors in spatial alignment of the various images.$^{13}$ Proper treatment of these effects is well-understood to be a difficult and open-ended problem that is spawning an ever-growing literature.$^{15,20–24}$

LOCI is also plagued by a problem that the community has come to appreciate only very recently, which is that the uncertainties have been greatly under-estimated due to the fact that small sample statistics have not been taken into account.$^{25}$ Briefly, the LOCI-processed image has residual speckles, whose amplitudes decrease with distance from the host star. In order to determine an uncertainty level as a function of radius, the amplitude of the speckles as a function of radial distance is estimated from the LOCI-processed image. However, speckles have a size of $\sim \lambda/D$, so, close to the host star there are very few speckles in a given small annulus. These small sample considerations lead to a statistical penalty that exponentially increases toward very small separations.$^{25}$

### 3. INFORMATION CONTENT OF MILLISECOND EXPOSURES

The idea of using millisecond exposures for ultra-high contrast imaging has been given little attention, mostly due to the fact that all of the current high-contrast efforts are based on longer exposures. The power of millisecond exposure analysis comes from two facts: 1) most of the atmospheric motion is nearly frozen on that time-scale and 2) the WFS provides a great deal of information about the AO residual. The key point is that at every millisecond the AO residual presents new random wavefronts. When combined with knowledge of the wavefront, each millisecond exposure provides more information about the NCPAs, due to the pinning effect.$^5$ This allows determination of the NCPAs without resorting to the LOCI-type procedures described in Sec. 2. In addition, the highly-informative, brief moments in which starlight happens to be greatly reduced (i.e., “dark speckles”$^{26}$) at the planet location can be fully exploited$^{27}$ as explained below.
Using a combination of the WFS and millisecond images from the science camera has been dubbed “random phase diversity,” and it has been explored by [27] and [28, 29]. In long-exposure imaging, far less information is available, as one only sees the time-average of all of the speckles, making the data from the WFS of little utility. Displaying a stellar coronagraph simulation result from [27], Fig. 3 shows two time series of the intensity seen in a single pixel of the science camera. The dotted curve illustrates how the AO residual modulates the stellar speckle at a cadence of 1 millisecond. The solid curve shows the much weaker modulation of the planetary light in the same pixel. These two time-series, the planetary intensity and the speckle intensity, are quite different in character, with the speckle having an approximately exponential probability density function (PDF), while the PDF of the planetary intensity is localized around its non-zero mean [27, 30]. This can be understood as follows: The planetary wavefront is stabilized by the AO system, as the flat part of the planet’s wavefront is responsible for its intensity at this position in the image plane. However, the speckle is entirely due to the random, non-flat part of the star’s wavefront (the coronagraph removes the flat part) and, hence, it is much more volatile. Taking advantage of the fleeting moments in which the starlight is reduced at the planet’s location, was first considered by Labeyrie [26] whose idea was to rely on statistics to determine how much of the remaining brightness was due to planetary emission. In the framework herein discussed, this task is greatly facilitated by knowledge of the wavefront and NCPAs.

Long-exposure observations have difficulty distinguishing amplitude NCPAs from phase NCPAs. Consider a pupil plane NCPA (upstream of the coronagraph) of the form \( \phi(r) = \alpha \cos(k \cdot r + \vartheta) \), where \( r \) is pupil plane coordinate vector, \( k \) is the vector spatial frequency of the aberration, \( \vartheta \) is the spatial phase, and \( \alpha \) is the complex amplitude of the aberration [1]. The imaginary part of the NCPA corresponds to an error in the wavefront amplitude and the real part corresponds to a phase error. However, millisecond observations clearly separate these effects, as is illustrated in Fig. 4 which simulates four different sinusoidal NCPAs all using the same AO residual as input. These four NCPAs all have the same spatial frequency \( k \), which places the two indicated speckles at a distance of about \( 4\lambda/D \) from the center. The top panels correspond to real NCPAs (\( \alpha \) is purely real), differing only in the phase angle \( \vartheta = (0, \pi/2) \). The bottom panels correspond to purely imaginary NCPAs (\( \alpha \) is purely imaginary), again differing only in the phase angle \( \varphi = (0, \pi/2) \). Of course, if the AO residual were precisely zero, all four of these NCPAs would lead to exactly the same two identical speckles. Standard long-exposure images cannot distinguish between these aberrations, although one could solve for them using well-calibrated offsets of the AO system’s deformable mirror, in a manner similar to the procedures given in [31, 32].

Thus, the pre-coronagraph, pupil plane field is modified by this NCPA via multiplication: \( E(r) \exp[j\phi] \), where \( E(r) \) would be the field without this NCPA.
Vibrations pose a particularly challenging problem to high-contrast astronomy. Since they are sensitive to specific conditions such as wind and thermal state of the system, they are difficult to characterize with reference images. Consider a vibration giving rise to an NCPA given by the form \( \phi(r) = \alpha \cos(k \cdot r + \omega t) \), where \( \omega \) is the vibration frequency and \( t \) is the time. Clearly, at millisecond time-scales, this NCPA will manifest a modulation in the science camera that depends on \( \omega \). Fig. 5 from [33], shows stellar coronagraph simulations demonstrating that the intensity time-series of the speckle associated with this NCPA is indeed strongly dependent on \( \omega \).

The most common objection to millisecond imaging methods is detector readout noise, which becomes a significant issue when the number of read-noise counts per pixel per exposure is comparable to, or greater than, the number of planetary counts per exposure. This intuitive notion was validated by simulations in [33], which also showed that the problem can be mitigated by combining exposures of various time-periods. By mixing various exposure lengths, one can use the information available at any time-scale (e.g., short exposures can uncover high-frequency vibrations, longer exposures can help to reveal weaker NCPAs and planets). This ability to self-consistently mix various exposure lengths makes detector noise no more consequential for the proposed methods than it does for the existing methods. Furthermore, we are entering an era of ultra-low noise IR cameras capable of kHz readouts, such as the SELEX APD (~ 2 e/pixel) and the MKIDS (single photon counting, with energy resolution) series, which includes DARKNESS and MEC [34, 35].

### 4. ESTIMATION PROCEDURES

Assuming knowledge of the wavefront, Frazin derived analytical expressions for simultaneously estimating the NCPAs and the planetary image from a time-series of stellar coronagraph images [27]. Consider the science camera producing a stream of data with pixel indices \((i, j)\) and frame index \(k\), so that \(i\) and \(j\) are spatial indices corresponding to image plane position \(\rho_{ij}\) and \(k\) corresponds to time \(t_k\). Then, the science camera data stream is denoted by the quantities \(\{I(\rho_{ij}, t_k)\}\). The essence of Frazin’s approach is to relate this data stream to a parameterized model of the NCPAs and the planetary image and
then determine the values of the parameters via statistical inference procedures. Frazin’s statistical inference problem is defined by the equation:

$$I(\rho_{ij}, t_k) = n(\rho_{ij}, t_k) + \mathcal{A}(\rho_{ij}, t_k) + \mathcal{B}(\rho_{ij}, t_k) \cdot a + \mathcal{C}(\rho_{ij}, t_k) \cdot a + \mathcal{F}(\rho_{ij}, t_k) \cdot p,$$

where the superscript $^H$ represents Hermitian conjugation, the planetary image is specified by the vector $p$ and the NCPAs (which may be time-dependent) are specified by the vector $a$. $a$ and $p$ are the only free parameters in the model. $a$ is vector of coefficient values, with each value controlling the strength of a given aberration function (e.g., a Zernike polynomial, but there is great flexibility here). Similarly, the planetary image is specified by the vector $p$, which may simply represent pixel values, but other options are available as well (e.g., 2D spline coefficients). $n(\rho, t)$ represents noise in the measurement, and should include the effects of shot noise, readout noise and thermal noise.

The $\mathcal{A}(\rho_{ij}, t_k)$ (scalar), $\mathcal{B}(\rho_{ij}, t_k)$ (vector), $\mathcal{C}(\rho_{ij}, t_k)$ (tensor) and $\mathcal{F}(\rho_{ij}, t_k)$ (vector) functions are much too complicated to present here, but they depend on the AO residual at time $t$, which comes from the WFS, as well as the telescope aperture function. Frazin’s formulation includes an idealized coronagraph, but that could be adjusted. $\mathcal{A}$ represents speckles due to the AO residual. The $\mathcal{B}$ terms account for the interaction of the NCPAs with the AO residual and aperture; they represent most of the “pinned” speckle. The $\mathcal{C}$ term accounts for 2nd order interaction of the NCPAs. $\mathcal{F}$ is called the “planetary intensity kernel” and describes the contribution of the planetary image. When a grid of points $\rho_{ij}$ are considered, this term becomes a convolution of the PSF with the planetary image. If no NCPAs are present (i.e., $a = 0$), estimating the planetary image $p$ reduces to a multi-frame deconvolution problem.

Note that Eq. (1) can be integrated in time (i.e., summed over $k$) to treat exposures of any duration in a fully self-consistent manner. Frazin gives numerical procedures to perform the interference, i.e., determine $a$, $p$ and their error bars in [27].

| variable | status | description |
|----------|--------|-------------|
| $I(\rho_{ij}, t_k)$ | measured | science camera intensity at pixel $(i,j)$ in frame $k$ |
| $a$ | inferred | coefficient vector of NCPA functions |
| $p$ | inferred | coefficient vector specifying planetary image |
| $A$ | modeled | speckle image of the star |
| $F$ | modeled | atmospheric speckle convolution kernel |
| $B, C$ | modeled | functions to describe “pinned” speckles |
| $n$ | modeled | random process describing noise in measurements |

Table 2. Statistical Inference via Eq. (1)

Is the new method better than LOCI?

Under the new paradigm, the planetary image is the result of a statistically optimal solution, not an ad-hoc background subtraction, as is the case with LOCI. This solution automatically includes the “dark speckle” concept described in Sec. 3 by optimally weighting the pixels according to the noise (bright pixels have more shot noise). Similarly, the counterpart to a “dark speckle,” in which a pixel is unusually bright (either due to a moment of low Strehl ratio, which makes the coronagraph ineffective, or simply to an inconvenient spatial frequency in the AO residual), is automatically given little weight.

‡The most common statistical inference procedure is weighted least-squares.
§Only the probability distribution of the noise $n$ is modeled, not any specific realization thereof.
Furthermore, including the diurnal rotation constraint (used by ADI), and spectral information (used by CDI and SD) is a straightforward extension of the basic method. Since the statistical inference is based on a tremendous amount of data, the small-sample statistics issues that plague LOCI (see Sec. 2 and [25]) do not arise. Thus, the only problem plaguing LOCI that has a counterpart under the new paradigm is possible frame alignment/registration issues, but there is no reason they should be worse. While at a theoretical level, there are no disadvantages to this new methodology, it does require a model of the optical system and a parameterization of the pupil-plane representation of the NCPAs so they can be represented by the vector of coefficients $a$. (Representing the planetary image with the vector $p$ is more straightforward, since $p$ may simply be a vector of pixel values.) Calculating the expected benefits of these procedures compared to LOCI is a difficult problem and cannot be done outside of the context of the long-term research effort. There are several reasons for this: 1) The wavefront measured by the WFS is hidden inside the $A, B, C$ and $F$ functions in Eq. (1) and propagating the 2nd order statistics of the wavefront to errors in the estimates of $a$ and $p$ requires specialized simulations. 2) The wavefront uncertainties themselves require a special effort to determine, as they have many causes ranging from shot noise and chromatic effects, to the temporal and spatial cut-off frequencies of the WFS. 3) The performance of the method depends on the type of NCPAs that are present. 4) The LOCI methods are hard to model and depend on a large number of factors.

5. PREVIOUS SUCCESS

Several groups have used millisecond exposures and (blind) deconvolution techniques to greatly surpass the resolution available from long-exposure imaging. As far back as 1997, Lee et al. used WFS measurements to solve for a NCPAs using on-sky data from the Starfire Optical Range, and, more recently, Codona et al. used on-sky data from the WFS on the MMT to solve for the complex amplitude of the turbulence-averaged diffraction pattern in the image plane. The stellar coronagraph simulations by Frazin in utilized measured wavefronts from the WFS on the AEOS Adaptive Optics System running at a frame rate of 1 kHz and included a sinusoidal NCPA that placed a speckle exactly coincident with a “planet” located at $\approx 3\lambda/D$ from the star. The star-to-planet brightness ratio was $10^5$, and at the planet’s pixel, the time-averaged speckle intensity was over 500 times brighter than the planet, so the planet was deeply buried in speckle noise and the shot noise. Using 4000 AEOS wavefronts (corresponding to 4 s of real time) the planetary intensity was correctly estimated with an error bar ±20%. Note that this simulation exercise did not include the constraints provided by diurnal rotation (used by ADI) nor any spectral information (used by SD and CDI).

6. IMPLICATIONS FOR EXTREMELY LARGE TELESCOPES

The potential to fully exploit the crucial information contained in millisecond exposures blurs the roles of the wavefront sensor and the science camera, opening a veritable Pandora’s box of profound issues.
Under the new paradigm of millisecond observations, the WFS is not simply a device used to control a deformable mirror (DM); it produces an information stream that is needed for further analysis. In particular, since the image data close to the star are sensitive to the wavefront’s high spatial frequencies due to a nonlinear effect called “frequency folding,” there is good reason to have a higher spatial and temporal bandwidth (the high spatial frequencies have shorter time-scales) than is required for DM control. Wavefront sensors capable of collecting data of maximal spatio-temporal bandwidth will require detectors without readout noise and more pixels, not to mention likely modifications to standard pyramid or Shack-Hartmann designs. Consideration must also be given to the role the science camera itself will have in wavefront sensing. How can the science camera data stream be used: 1) to mitigate chromatic effects caused by the WFS and science camera operating at different wavelengths? 2) to improve the AO control loop (particularly for low-order aberrations)? 3) to monitor the real-time state of the telescope for vibration detection? There will also be significant motivation to collect spectral information in the science channel at millisecond time resolution, thus designs for photon-counting, energy-resolving IR detectors and integral field spectrometers capable of millisecond readout rates need to be evaluated. Since such considerations have very significant design and cost implications, it is best to investigate them as soon as possible, while the ELTs are still in the early stages of development.

7. CONCLUSION

The goal of making a direct image of a habitable planet will require telescope imaging systems to achieve unprecedented contrast levels. All current efforts in ultra-high contrast imaging require subtracting a background image that is very difficult to estimate, a fact to which the ever-growing literature on the subject attests. Recently, and proposed a paradigm-shifting method that does away with background subtract altogether in favor a rigorous statistical inference procedure that estimates the NCPAs simultaneously with the planetary image. and provided simulation results in which a planetary brightness was correctly estimated, despite the fact that the planet was exactly spatially coincident with a speckle. Similar results are not theoretically possible with current LOCI procedures because did not take advantage of spectral or angular diversity, which are the primary sources of information used by LOCI methods. Rather, and obtained the required information from the random phase diversity provided by the turbulent atmosphere at millisecond time-scales. It is important to note that generalizing the method introduced in to include angular and spectral diversity is a straightforward matter. The implication is that, on a theoretical level, there is no disadvantage to using the methods of compared to current LOCI methods, and there is much to gain from the millisecond information, as described in Sec. As the new methods blur the roles of science camera and wavefront sensor, optimizing these systems for ultra-high contrast imaging needs to be studied, as the conclusions of such studies are likely to have profound implications for ELT hardware, if ultra-high contrast imaging is going to be high-priority science with ELTs.

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