Wavefront control for high-contrast imaging

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*In the Spirit of Bernard Lyot: The direct detection of planets and circumstellar disks in the 21st century.*

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We need wavefront control

- Coronagraph can reduce diffracted star light
- Wavefront control can reduce light scattered by wavefront phase and amplitude errors

Figure taken from J. T. Trauger and W. A. Traub, “A laboratory demonstration of the capability to image an earth-like extrasolar planet,” Nature 446, 771–773 (2007).
Two aspects to PSF after wavefront control

- The level of scattered light must be low
- The variance of the scattered light must be low

GPI with H-band APLC, 14.5 cm $r_0$, $l=6$

0.0625 sec

12 sec
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GPI with H-band APLC, 14.5 cm \( r_0 \), \( I=6 \)

Planet is \( 10^6 \) times dimmer

0.0625 sec

12 sec
PSF expansion allows analysis of structure

- Express amplitude and phase with Taylor expansion:
  \[ a \exp(j\phi) = a \left(1 + j\phi - \frac{\phi^2}{2} + \cdots\right) \]

- Image plane field is convolutions of Fourier transforms:
  \[ A + jA \star \Phi - \frac{1}{2}A \star \Phi \star \Phi + \cdots \]

- Image plane intensity has several important terms:
  - Diffraction pattern: \(|A|^2\)
  - Pinned speckles: \(-2\text{Im}\{A^*(A \star \Phi)\} - \text{Re}\{A^*(A \star \Phi \star \Phi)\}\)
  - Power Spectrum (PSD): \(|A \star \Phi|^2\)
  - Folding term: \(\frac{1}{4}|A \star \Phi \star \Phi|^2\)

Power spectral approach for random errors

- Evaluate PSD term of PSF expansion
- This tells us the expected halo intensity in an infinitely long exposure
- Several treatments exist, including Ellerbroek; Guyon; Jolissaint *et al*

Figure 2. Aliasing power spectrum (1/8 power-law scaling) within the LF domain; see parameters in Table 1.

Phase control with conjugation on DM surface

- Measure and compensate the phase
Fitting error due to uncorrected HSF phase

- Uncorrectable errors beyond spatial freq. range of DM
  - Atmosphere
  - Optics
- HSF limits contrast outside dark hole
- HSF phase may limit contrast inside dark hole due to folding term
- Ways to improve:
  - smaller inter-actuator spacing
  - better site (higher r0)
  - better optics

Atmospheric fitting error

1e-6 1e-4
HSF phase also can cause aliasing

- Sampling the phase produces aliasing when HSF content exists
- These incorrect measurements lead to significant error
- Ways to improve:
  - Spatially Filtered wavefront sensor (700-900 nm shown)
  - Focal-plane wavefront sensor
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Control system delays cause temporal error

- Controller has delays which lead to error when correcting a dynamic aberration
- PSD level depends on total power and temporal characteristics of aberration
- Ways to improve:
  - Reduce delay from measurement to application of correction
  - Better control algorithms

AO on five-layer frozen flow atmosphere
Modal control with gain optimization

- Use closed-loop telemetry to optimize performance based on atmospheric characteristics and SNR
  - Used currently in NAOS, Altair, and Keck AO Tip/tilt
  - SPHERE will use modal gain optimization
  - GPI will use modal gain optimization of the Fourier modes (spat. freqs)
Predictive control based on Kalman filtering

- Given a model and a framework (e.g. Kalman filtering), determine predictive control law to compensate for system lags and phase dynamics.
- Vibration control for SPHERE experimentally demonstrated.
- Developed for GPI: Kalman filtering for each Fourier mode, based on frozen flow assumption. Adaptive layer detection and predictive filter determination in closed-loop. Performance improvement depends on true atmospheric behavior, which is being actively researched.
Fourier mode behavior under translation

22.7 m/s 3.28 m/s 16.6 m/s 5.89 m/s 19.8 m/s

41.1 Hz -5.76 Hz 11.7 Hz 3.06 Hz -33.1 Hz
Measurement noise propagates

Shack-Hartmann WFS noise propagation

- Noise of phase/slope measurements, due to photons and detector noise

- Ways to improve:
  - Better detectors (higher efficiency, lower read noise)
  - Better WFS slope estimation algorithms
  - Better AO control algorithms
  - Different wavefront sensor
Pupil-plane slope sensor

- Implementation options:
  - Shack-Hartmann: inexpensive, widely used (both GPI and SPHERE)
  - Pyramid slope sensor: starting to be implemented, requires modulation
- Significant aliasing error, but can be fixed with Spatial Filter
- Noise propagation is non-white: $f^{-2}$

[Images: Aliasing (atmos.) and Noise halo]
Pupil-plane direct phase sensor

• Multiple options (see Guyon’s paper for many)
  • Interferometer
  • Zernike phase contrast
  • Pyramid in direct phase mode

• Less aliasing error
• White propagation: $f^0$

Aliasing (atmos.)  Noise halo
Pupil-plane direct phase sensor

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Two advantages over slope sensing:
1) less total noise as system size increases
2) flat noise profile, so better detection close in after control optimization

Aliasing (atmos.)

Noise halo
Long-exposure PSF halo prediction for GPI

- GPI has two different AO simulators
  - analytic PSD code
  - end-to-end Fourier Optics monte carlo which simulates entire AO system
- These two methods are in agreement
- Example shown:
  - I=6, five-layer 14.5 cm r0 atmosphere, 2 kHz, Optimized-gain controller, 700-900 nm WFS, APLC at 1.625 microns, 5 second exposure
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GPI should improve upon general-purpose AO

PSD term of PSF, 14.5 cm r0, SNR ~ 10

Intensity (APLC normalized)
Angular separation (arcsec)

Altair
GPI

PSD term of PSF, 14.5 cm r0, SNR ~ 10

0.01
0.001
0.0001
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}

0.1
1

Angular separation (arcsec)
Additional error terms must be considered

- The previous four errors (along with anisoplanatism) form a set of “classic” AO errors.
- For high-contrast imaging we need to assess impact of more subtle errors, as was done by Guyon.

Amplitude errors (scintillation)

- Amplitude errors are not corrected with phase conjugation
- Possible sources
  - Scintillation as light propagates through atmosphere
  - Reflectivity variations on optics
  - Phase errors on out-of-plane optics
- Ways to improve:
  - Correct amplitude with DM(s)
  - Improve quality of optics

Uncorrected atmospheric scintillation

1e-9 to 1e-5
Control is not limited to phase conjugation

- Shape DM with a phase that does not conjugate
- Use of a single DM for amplitude and phase produces a half dark hole
- Use of multiple DMs for amplitude and phase produces a full dark hole
- See talks later this session

Fig. 2. Wavefront control system now consists of one DM located at a pupil image (DM_p) and a second one, DM_{np}, a distance z_{DM} downstream. DM_p controls phase, while DM_{np} controls amplitude. Both the phase-induced amplitude from the optical surface errors and the amplitude control using DM_{np} are wavelength independent.

Figure taken from S. B. Shacklan and J. J. Green, “Reflectivity and optical surface height requirements in a broadband coronagraph. 1. Contrast floor due to controllable spatial frequencies”, Appl. Opt. 45, p 5143-5153 (2006)
Image plane wavefront sensing/control

- Sensing strategy usually directly tied into the control algorithm
- Advantages
  - Everything is “common-path”, same wavelength
  - Aperture provides anti-aliasing, provided adequate pixel size
  - Can be easily used in an amplitude-and-phase correction method
- Disadvantages
  - Requires very good correction already (e.g. Bordé & Traub’s speckle nulling assumes $\lambda/1000$ aberrations)
  - Are detectors available which have low noise at the necessary frame rates?
  - Limited to narrow-band operation (sensing and correction algorithms)
WFS not at science wavelength

Chromatic terms arise when behavior is a function of wavelength
- Fresnel propagation
- Change in index of refraction
- Change in pupil position due to DAR

Ways to improve:
- Don’t use very blue light (400 nm)
- Use science light for WFS

Atmosphere, 700-900 nm WFS, 1600 nm science
WFS not at science wavelength

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Only scintillation may matter for GPI
Temporal structure of PSF

• What we’ve shown so far has focused on the expected intensity (infinitely long exposure level)

• In reality, we have shorter exposures, and speckles from different error sources behave in different ways
  • WFS noise
  • atmosphere
  • quasi-static error

• 10’s of nm of a rapidly decorrelating error may be better than 1’s of nm of a slowly varying one
Wavefront sensor noise is nearly white

- WFS noise input is assumed to be temporally white
- WFS noise output of control system is nearly white
Wavefront sensor noise is nearly white

- WFS noise input is assumed to be temporally white
- WFS noise output of control system is nearly white

GPI with H-band APLC, 10 msec exposures at 100 Hz
Intensity converges with longer exposures

Intensity of a single speckle, tracked over five different exposures

Intensity converges with longer exposures
Noise speckle variance drops rapidly
Atmospheric error is dominated by wind

- Clearing of wind over aperture $\frac{D}{v}$ sets decorrelation time
Atmospheric error is dominated by wind

- Clearing of wind over aperture $\frac{D}{v}$ sets decorrelation time

GPI with H-band APLC, 10 msec exposures at 100 Hz
Atmospheric speckles evolve more slowly
Dominant term depends on exposure time
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Static errors “print through”

- 10 nm of static error appears above noise halo
Static errors “print through”

- 10 nm of static error appears above noise halo
Static and Atmospheric speckle noise in 2-hour GPI exposure

Figure courtesy of C. Marois; from the Gemini Planet Imager Preliminary Design Report (2007)

Static errors on optics important for GPI
### Two scenarios with distinct characteristics

<table>
<thead>
<tr>
<th></th>
<th><strong>Ground</strong></th>
<th><strong>Space</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Phase errors</strong></td>
<td>Rapidly varying atmospheric error dominates; also smaller and slowly varying optical errors</td>
<td>Slowly varying; due to optics</td>
</tr>
<tr>
<td><strong>Amplitude errors</strong></td>
<td>Much less significant; due to atmosphere and optics</td>
<td>Slowly varying; due to optics</td>
</tr>
<tr>
<td><strong>WFS</strong></td>
<td>Pupil-plane; slope sensor in near term, direct-phase in future</td>
<td>Image-plane WFS in science path</td>
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<tr>
<td><strong>WF control</strong></td>
<td>DM for phase control only</td>
<td>Phase and amplitude control with 1 DM (half-dark hole) or 2 DMs (full dark hole)</td>
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<tr>
<td><strong>Time frames</strong></td>
<td>&gt; 1 kHz</td>
<td>&gt; 1 milliHz</td>
</tr>
<tr>
<td><strong>Telescope size</strong></td>
<td>8-10m now, 20-30m future</td>
<td>1-4 m?</td>
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Need to control PSF to be dim and smooth

- Wavefront control is essential for high-contrast imaging
- Intensity (infinite-exposure case) can be addressed through analytic tools
- Planet detectability with exposure time depends on temporal character of error sources

Figure courtesy of A. Sivaramakrishnan from Oppenheimer (in preparation 2007)