Direct imaging of exoplanets: signal and image processing advances

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CASIS Workshop
May 23, 2012

LLNL-PRES-558414
Ground-based images of planets

Image credits: HR 8799: C. Marois, Keck Obs.; NASA HST; Beta Pictoris: M. Lagrange, ESO
We want photons from the planet

- Indirect methods give us orbit, mass (and sometimes size)
- Claims on habitability are speculation (Earth vs Venus)
- Spectroscopic measurements of planetary light can tell us about temperature, chemistry, gravity...

Adaptive optics removes the blur

- Corrects atmospheric turbulence in astronomy
- Corrects aberrations in the eye in vision science

Image credits: Galactic Center: A. Ghez (UCLA), Keck Obs.; Retina: A. Roorda (UCB)
Measure and conjugate the phase
Block the star light

- Use a coronagraph to suppress diffraction
- Standard design by Lyot
- Many modifications and alternatives available (e.g. prolate spheroids) ...

Image credits: Eclipse: DeviantArt.net; PSFs: Bruce Macintosh
Diversity improves detections

- As the telescope tracks, the planet moves ("roll deconvolution": Sparks or "ADI": Marois)
Diversity improves detections

- The position of the star and planet remain stationary with wavelength, but speckles move ("SDI": Racine, Marois)

Simulation utilizes the GPI Data Simulator (thanks to J. Maire and M. Perrin)
HR 8799... and beyond

All images/simulations courtesy of Christian Marois (HIA)
Gemini Planet Imager

• GPI is a science experiment: 890 hours for a three-year survey of 600 target stars
• World’s most advanced AO system
• Improved Lyot coronagraph
• Integral field spectrograph for detection and characterization
• Calibration interferometer for low static error

Spatial filter photo from S. Thomas and B. Macintosh; PPM image courtesy of R. Soumer; IFS optics test images from U. Montreal.
Reconstruct in Fourier space

WFS x-slopes
WFS y-slopes
Solve boundary problem
FFT
FFT
Recon. filter

Desired phase (actuators)

\[ \frac{1}{1 - z^{-1}} \]

FFT-1

Eigen functions that correspond to locations in the image

Gain filter

Complex-valued Fourier coefficients

1
-1
Data-driven optimization

\[ \text{WFS } x\text{-slopes} \quad \text{WFS } y\text{-slopes} \]

\[ \text{Solve boundary problem} \]

\[ \text{FFT} \quad \text{FFT} \]

\[ \text{Periodograms} \]

\[ \text{Recon. filter} \]

\[ \text{Optimize gains} \]

\[ \text{PSDs} \]

\[ \frac{1}{1 - z^{-1}} \]

\[ \text{FFT}^{-1} \]

\[ \text{Gain filter} \]

\[ \text{Complex-valued Fourier coefficients} \]
Use a control system model

• Model and verify control system behavior using Z- or Laplace transforms
• Use wavefront residuals during operation to estimate signal and noise temporal power spectra
• Find best gain by minimizing error power

\[
\arg\min_{C(z)} \left\{ \int_{-\pi}^{\pi} \frac{1}{1 + \exp(-2j\omega)C(\omega)}^2 \left| 1 + \exp(-j2\omega)C_0(\omega) \right|^2 \hat{P}_{y,cl}(\omega) d\omega \right\}
\]
As-built system matches model

- Estimate ETF as ratio of open/closed loop measurements
- We have a detailed Laplace model of system dynamics
- Excellent agreement of model and calibration with measured data

From I=7.2 test case
Gain optimizer working correctly

- Updates gains every 10 seconds
- Converges rapidly to correct modal gains and stays there
- Even did the right thing when we accidentally spun the phase plate to make 80 m/s wind!

*Testing with same spinning phase plate*
Gain optimization in action

- Bright star case
- Gains 0.1 to start
  - WFS measures 45 nm RMS
- The optimizer increases the gains to 0.3 for nearly all modes
  - WFS measures 24 nm RMS
From detection to estimation

- Several key parameters we want to do science with
  - astrometry
  - photometry
  - spectral estimation

Movie courtesy Q. Konopacky (now at U. Toronto)
Separating planet from speckle

- Integral field spectrograph produces a datacube of x-y-λ
- Standard detection algorithm (LOCI) introduces artifacts

HR 8799 Keck observational data from B. Macintosh
Linear fitting algorithm

- Use a model-based linear fitting algorithm to remove speckles without biasing planet signal
- Still in progress...
GPI is nearly complete
On the horizon...

- Slowly-varying errors at the 1-5 nm level limit our performance - how to reduce these? Can we use correlations over many observations for behavior such as gravity-induced beam shear?

- Laboratory and then on-sky testing of Predictive AO control (frozen flow atmosphere) to further reduce residual error