On Advanced Estimation Techniques for Exoplanet Detection and Characterization using Ground-based Coronagraphs

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and the NAKFI Exoplanet Imaging Group
Overview of Presentation

• The State of the Art in Exoplanet Imaging
  – Strengths and weaknesses of LOCI
• The Hotelling Observer
• Receiver Operating Characteristic
• Formal Evaluation of Imaging Algorithms
  – An Exoplanet Imaging Challenge
• Summary and Perspective
Left to Right:
Harrison Barrett (Univ. Arizona)
David Mouillet (Grenoble)
Szymon Gladysz (Fraunhofer Inst)
Luca Cau (Univ. Arizona)
Lars Furenlid (Univ. Arizona)
Laurent Mugnier (ONERA)
Dmitry Savransky (LLNL)
Lisa Poyneer (LLNL)
Laurent Pueyo (Johns Hopkins)
Peter Lawson (JPL)
Dimitri Mawet (ESO)
Nicholas Devaney (Univ. Galway)
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Not pictured:
John Krist (JPL)
Olivier Guyon (Univ. Arizona)
Christian Marois (HIA/NRC)
Rémi Soummer (STScI)

Additional support from:
Marshall Perrin (STScI)
Jérôme Maire (Univ. Toronto)
New Ground-based Exoplanet Instruments 2012-2020

Extreme AO on 8–10-m class telescopes

- Palomar P1640
- Gemini Planet Imager
- ESO VLT-SPHERE
- Subaru SCExAO

Extreme AO on Extremely Large Telescopes (30–42m diameter)

- Thirty Meter Telescope
- European Extremely Large Telescope
- Giant Magellan Telescope
### Some Demographics

#### Astronomers / Experimentalist

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Names</th>
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</table>
| SPHERE     | David Mouillet (Grenoble)  
Dimitri Mawet (ESO) |
| GPI        | Christian Marois (HIA/NRC)  
Lisa Poyneer (LLNL)  
Laurent Pueyo (Johns Hopkins) |
| P1640      | Rémi Soummer (STScI)  
Laurent Pueyo (Johns Hopkins) |
| SCExAO     | Olivier Guyon (Univ. Arizona) |
| JWST       | John Krist (JPL) |

#### Imaging Experts / Theoreticians

<table>
<thead>
<tr>
<th>Institution</th>
<th>Names</th>
</tr>
</thead>
</table>
| University of Arizona | Harrison Barrett (Univ. Arizona)  
Luca Cauci (Univ. Arizona)  
Lars Furenlid (Univ. Arizona) |
| Fraunhofer Inst. | Szymon Gladysz (Fraunhofer Inst) |
| ONERA        | Laurent Mugnier (ONERA) |
| Lawrence Livermore Nat. Lab. | Dmitry Savransky (LLNL) |
| University of Galway | Nicholas Devaney (Univ. Galway) |
Preamble
State of the Art: Ground Observations
Locally Optimized Combination of Images (LOCI)

K-band, 10s exposure
68 coadded

~10x improvement per image, then \(~\sqrt{n}\).
For 100 images, gain of the order of 50-100x (5 mag).

Movie...

Courtesy of Christian Marois (NRC, Herzberg Institute of Astrophysics, Canada)
The Hotelling Observer

- Based on 1931 paper by Harold Hotelling
- Performs only linear operations on data
- Optimum in several senses
- Requires knowledge of ensemble mean and covariance of the images
- Computational difficulty: inversion of large covariance matrix (but many tricks available)
- Equivalent to ideal observer for Gaussian data

Harold Hotelling (1895–1973)

The Hotelling Template

Linear discriminants all have the form of a scalar product:

\[ t(g) = w^t g, \]

where \( w \) is a template vector the same size as data \( g \),

The Hotelling template is the one that maximizes the SNR:

\[ \text{SNR}_t = \frac{\langle t \rangle_+ - \langle t \rangle_-}{\sqrt{\frac{1}{2} \sigma_+^2 + \frac{1}{2} \sigma_-^2}} \]

For weak signals, the data have equal covariance \( K_g \) under the two hypotheses, and the optimal template is

\[ w_{Hot} = K_g^{-1} \Delta \bar{g}, \]

where \( \Delta \bar{g} \) is the average difference in the data under the two hypotheses, averaged over all sources of variability.

The resulting SNR is then given by

\[ \text{SNR}_{Hot}^2 = \Delta \bar{g}^t K_g^{-1} \Delta \bar{g} \]
Comments on the Covariance Matrix $K_g$

- It’s huge! (# pixels × # pixels for one image)
- It’s an ensemble covariance matrix, not a sample matrix
- It must include all sources of randomness, at least in the signal-absent images
- It must be inverted to get the Hotelling template
Receiver Operating Characteristic (ROC)

- The ROC curve quantifies the relative performance of different imaging algorithms.
- Example on the right by Caucci, et al.

Example: Gemini Planet Imager

- Southern Hemisphere, 8-m telescope
- Calibration interferometer
- 64x64 Boston Micromachines DM (tweeter)
- Suspended under the telescope: mass and volume constrained
- Closely similar design to Palomar P1640
Imaging Challenge: Phase I

- Simulated data from the GPI Integral Field Spectrograph
- H band
- 281 x 281 pixels
- 5 wavelength channels
- Atmospheric turbulence
- Extreme AO corrected
- **No Talbot effects**
- 30 s integrations
- 1 hour of data (120 images) per simulated planetary system
- 100 simulated planet systems
Sample Processed LOCI Map

- Results from data processing with the Hotelling observer are still in process
- Shown on the right is a processed image by Dmitry Savransky (LLNL) using his version of LOCI
- Performance statistics are shown on the following page
Initial Results with LOCI Processing
Lisa Poyneer & Dmitry Savransky (LLNL)

- Stellar magnitude of 5
- 95 of challenge datasets analyzed, producing a single processed image for each
- Automatically identifying planets (correct size, ignoring streaks in image)
- Adjusting the detection threshold and counting true positives and false positives
- A black dot identifies a planet in the data
- Bare dots are planets that are not found or outside of search area
- The size of the circle is proportional to the detection threshold at which the planet was found
- The color of the circle indicates # of false positives at that threshold
Summary and Perspective

• Our goal is to test the potential of new imaging algorithms and in particular to show advances over the current state of the art demonstrated by LOCI.

• We have established a large collaboration including representatives from all near-term coronagraph projects (P1640, GPI, SPHERE, and SCExAO).

• We have agreed on a path forward to evaluate and test new algorithms through a formal Exoplanet Imaging Challenge.

• We have produced a first archive set of simulated data, representing exoplanets observed with the Gemini Planet Imager.

• Preliminary results are now allowing us to quantify the performance of LOCI.

• We are looking forward to evaluate results using the Hotelling Observer and possibly other algorithms.

• After a second phase of study, our final results will be published in the refereed literature.
Acknowledgements

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