Determination of astrometry and photometry of faint companions in the presence of residual speckle noise

1Daniel Burke
1Nicholas Devaney
& 2Szymon Gladysz

1Applied Optics Group
School of Physics
National University of Ireland
Galway
2ESO
daniel.burke@nuigalway.ie

June 26, 2009
Overview

- Problem Statement
- The Hotelling Observer
- PSF Reconstruction using Wavelength Diversity
- Data Simulation
- The Algorithm
- Results
- Conclusions and Future Work
Problem Statement

Differential astrometry and photometry of faint companions is difficult due to:

- the high contrast ratio between the parent star and the companion and
- the presence of residual quasi-static speckles
Problem Statement

Differential astrometry and photometry of faint companions is difficult due to:

- the high contrast ratio between the parent star and the companion and
- the presence of residual quasi-static speckles

We propose to use a combination of:

- Differential Imaging
- PSF reconstruction from wavelength diversity and
- The Hotelling Observer
Prewhitening matched filter
Prewhitening matched filter

A likelihood based approach
The Hotelling Observer

- Prewhitening matched filter
- A likelihood based approach
- Our data covariance model requires a good PSF estimate
\[ t(g) = sK_g^{-1}g \]  

- \( s \) is our model of the exoplanet signal
- \( K_g \) is the data covariance matrix
- \( g \) is the observed data
The PSF Estimate is used in the Hotelling framework to:

Raw Image
The PSF Estimate is used in the Hotelling framework to:

- **Raw Image**
- **PSF Subtracted**
The PSF Estimate is used in the Hotelling framework to:

- Raw Image
- PSF Subtracted
- Prewhitened Data
The PSF Estimate is used in the Hotelling framework to:

- **Raw Image**
- **PSF Subtracted**
- **Prewhitened Data**
- **Hotelling Observer**
The performance of the Hotelling Observer was compared to StarFinder and Fitstars.
The performance of the Hotelling Observer was compared to StarFinder and Fitstars.

For details see Burke et al. 2009 (Accepted to PASP).
The performance of the Hotelling Observer was compared to StarFinder and Fitstars.

For details see Burke et al. 2009 (Accepted to PASP).
• Estimate the phase at the pupil from focal plane intensity measurements
PSF Reconstruction using wavelength diversity

- Estimate the phase at the pupil from focal plane intensity measurements
- In classical phase diversity two images are recorded: one in focus and the second with a known amount of defocus
Estimate the phase at the pupil from focal plane intensity measurements.

In classical phase diversity two images are recorded: one in focus and the second with a known amount of defocus.

We utilise difference in $\lambda$ in multi-wavelength data to retrieve unknown phase e.g. SDI or IFS.
PSF Reconstruction using wavelength diversity

- Estimate the phase at the pupil from focal plane intensity measurements
- In classical phase diversity two images are recorded: one in focus and the second with a known amount of defocus
- We utilise difference in $\lambda$ in multi-wavelength data to retrieve unknown phase e.g. SDI or IFS
- The Gonsalves least squares phase diversity approach was used to estimate the phase of the WF (Gonsalves (1982))
Zernike polynomials were used to expand the phase over a circular pupil.
Zernike polynomials were used to expand the phase over a circular pupil

The solution to the problem is found by estimating an aberration vector which the minimizes an objective function
Zernike polynomials were used to expand the phase over a circular pupil.

The solution to the problem is found by estimating an aberration vector which the minimizes an objective function.

In practice this aberration vector is found through numerical, non-linear minimisation of the objective function.

For details see Lee et al. 1997.
Simulating an ELT: PAOLA (Jolissaint et al. 2006)

- End-to-End AO Simulation
- Based on an analytical description of the residual phase spatial power spectrum
- 42m primary modelled with an 12.5m central obstruction and four spider arms
End-to-End AO Simulation

Based on an analytical description of the residual phase spatial power spectrum

42m primary modelled with an 12.5m central obstruction and four spider arms
Simulating an ELT: PAOLA (Jolissaint et al. 2006)

- End-to-End AO Simulation
- Based on an analytical description of the residual phase spatial power spectrum
- $42\,m$ primary modelled with an $12.5\,m$ central obstruction and four spider arms
Two rotating data sets at 1.64\(\mu m\) and 1.8\(\mu m\).
Two rotating data sets at 1.64\(\mu m\) and 1.8\(\mu m\)

The companion is bright in the 1.64\(\mu m\) data set \(\Delta m = 10\)
Two rotating data sets at 1.64µm and 1.8µm.

The companion is bright in the 1.64µm data set $\Delta m = 10$ and dim in the 1.8µm data set $\Delta m = 15$. 

---

**Daniel Burke**

Determination of astrometry and photometry of faint companions
For each angle, wavelength diversity is used to estimate the PSF.
The Algorithm

- For each angle, wavelength diversity is used to estimate the PSF
For each angle, wavelength diversity is used to estimate the PSF

Bright companion
The Algorithm

- For each angle, wavelength diversity is used to estimate the PSF

Bright companion  Faint companion
For each angle, wavelength diversity is used to estimate the PSF
The Algorithm

- The image sequence is then derotated and coadded.
The image sequence is then derotated and coadded.
The image sequence is then derotated and coadded.

The Hotelling Observer shows a clean maximum.
The Algorithm

- The image sequence is then derotated and coadded
- The Hotelling Observer shows a clean maximum
Results: Astrometry and Photometry

\[ \hat{r}_{\text{companion}} = 0.046 \text{ arcsec}, \ r_{\text{companion}} = 0.0442 \text{ arcsec} \]
$r_{\text{companion}} = 0.046 \text{ arcsec}, \ r_{\text{companion}} = 0.0442 \text{ arcsec}$

$\Delta \hat{m}_{\text{companion}} = 10.4, \ \Delta m_{\text{companion}} = 10$
Conclusions

In the presence of residual speckle noise our combination of techniques has been shown to be able to detect faint companions, down to $\Delta m = 10$.

Accurate astrometry and photometry was also extracted for the faint companion.

Future Study

- Utilise a better phase retrieval algorithm to reconstruct the PSF.
- Test the approach with fainter and closer companions.
- Extend approach to IFS.

Daniel Burke

Determination of astrometry and photometry of faint companions.
Conclusions and Future Study

Conclusions

- In the presence of residual speckle noise our combination of techniques has been shown to be able to detect faint companions, down to $\Delta m = 10$

Future Study

- Utilise a better phase retrieval algorithm to reconstruct the PSF
- Test the approach with fainter and closer companions
- Extend approach to IFS
Conclusions and Future Study

Conclusions

- In the presence of residual speckle noise our combination of techniques has been shown to be able to detect faint companions, down to $\Delta m = 10$
- Accurate astrometry and photometry was also extracted for the faint companion

Future Study

- Utilise a better phase retrieval algorithm to reconstruct the PSF
- Test the approach with fainter and closer companions
- Extend approach to IFS
Conclusions and Future Study

Conclusions

- In the presence of residual speckle noise our combination of techniques has been shown to be able to detect faint companions, down to $\Delta m = 10$
- Accurate astrometry and photometry was also extracted for the faint companion

Future Study

- Utilise a better phase retrieval algorithm to reconstruct the PSF
- Test the approach with fainter and closer companions
- Extend approach to IFS
Conclusions and Future Study

**Conclusions**
- In the presence of residual speckle noise our combination of techniques has been shown to be able to detect faint companions, down to $\Delta m = 10$
- Accurate astrometry and photometry was also extracted for the faint companion

**Future Study**
- Utilise a better phase retrieval algorithm to reconstruct the PSF
Conclusions and Future Study

Conclusions

- In the presence of residual speckle noise our combination of techniques has been shown to be able to detect faint companions, down to $\Delta m = 10$
- Accurate astrometry and photometry was also extracted for the faint companion

Future Study

- Utilise a better phase retrieval algorithm to reconstruct the PSF
- Test the approach with fainter and closer companions
Conclusions and Future Study

**Conclusions**
- In the presence of residual speckle noise our combination of techniques has been shown to be able to detect faint companions, down to $\Delta m = 10$.
- Accurate astrometry and photometry was also extracted for the faint companion.

**Future Study**
- Utilise a better phase retrieval algorithm to reconstruct the PSF.
- Test the approach with fainter and closer companions.
- Extend approach to IFS.
Thank you...

Questions?