Super-resolution imaging with an ELT: Kernel-phase interferometry

\[ I = O \otimes \text{PSF} \]

\[ \Phi = \Phi_0 + A.\varphi \]

At high Strehl
How not to solve the full problem!

Find an operator $K$ so that:

$$K \phi = K \phi_0 + K A \varphi$$

$K \phi = K \phi_0$

$K$ is the kernel of $A$

$K \phi$ are called kernel-phases

Closure-phase: a special case of Kernel

\[ \Phi(1-2) = \Phi(1-2)_0 + (\Phi_1 - \Phi_2) \]
\[ \Phi(2-3) = \Phi(2-3)_0 + (\Phi_2 - \Phi_3) \]
\[ \Phi(3-1) = \Phi(3-1)_0 + (\Phi_3 - \Phi_1) \]


By the way, closure phase has detected planets...

Data analysis

1. Build a instrument model => A
2. Find the Kernel of A: K
3. Fourier Transform each image
4. Extract phase $\phi$

5. Multiply $K \phi$: you are done!

Additionally:
- statistics
- model the data (e.g. binary)
- determine contrast limits

http://code.google.com/p/pysco/

Monday, May 27, 2013
First ground based Ker-phase detection

- Separation: 136.1 +/- 3 mas
- Position Angle: 274.6 +/- 2 deg
- Contrast: 23.6 +/- 4

Data, courtesy of S. Hinkley
Martinache, 2013, 221st AAS conference

Re-analysis of NICMOS I data

Data @ 1.9 μm (λ/D=150 mas)

A ~10:1 contrast companion to a nearby M-dwarf identified with **milli-arc-second precision** at 0.5 λ/D


**Original survey:**
*Reid et al, 2006, 2008*

Revisit ~ 80 brown dwarfs observed with HST/NIC1 in the F110W and F170M filters

- Doubled the fraction of known L-dwarf binary systems
- Improved astrometry x10

Grant HST-AR-12849.01-A

Contrast detection performance?

Orthogonal kernel-phases
De-correlated signals, but not necessarily de-correlated noises


Statistically independent kernel-phases
Taking into account data covariance translates into improved contrast detection limits

For wavefront sensing purposes, need to maximize the number of non-singular values of $A$.

Introduce some **asymmetry** in the pupil suffices in making the matrix invertible.

Eigen modes of the PSF Fourier transform

Limitation: restricted to initial Strehl $\sim 50\%$.

Application for now restricted to the non-common path error calibration in XAO systems, but can be extended.

*Martinache, 2013, PASP, 125, 422*
Focal plane based wavefront sensing

Because it is a focal plane based sensing technique, sensitivity is set by the diffraction limit. Performance is particularly good for the low order modes... good for small IWA coronagraphy.

Martinache, 2013, PASP, 125, 422
- Very low impact - high payoff
- Asymmetric masks (at two different azimuths) in a pupil wheel after the SCExAO DM inside the instrument.
- Preliminary experimental result shows that the sensor works.
- Ongoing work toward a close-loop system for the non-common path error calibration on SCExAO.
- Close-loop on-sky demonstration?

[Link](http://www.frantzmartinache.com/subaru/02projects/03kerphi/02wfs/02wfs.html)
Interferometric imaging with an ELT

Example of super-resolution image with Keck @ 2.3 μm Using NRM-interferometry (λ/D = 45 mas).


With a 30-meter aperture, interferometric imaging on an ELT offers an incredible opportunity to obtain very high resolution images of complex sources.

This sort of imaging relies on non-redundant masks and is therefore compatible with even seeing limited observations.

But with AO on an ELT, redundancy is no longer a strict requirement...

Golay, 1971, JOSA, 61, 272
ELT pupil optimized for imaging

G12

Full

Ring

A fully redundant array is not optimal here...

<table>
<thead>
<tr>
<th></th>
<th>Golay 12</th>
<th>Full</th>
<th>Ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>nA</td>
<td>12</td>
<td>27</td>
<td>15</td>
</tr>
<tr>
<td>nuv</td>
<td>66</td>
<td>108</td>
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</tr>
<tr>
<td>nK</td>
<td>55</td>
<td>49</td>
<td>85</td>
</tr>
<tr>
<td>% info</td>
<td>51%</td>
<td>45%</td>
<td>79%</td>
</tr>
</tbody>
</table>

The Ring pupil gives the same uv-coverage, but recovers a higher fraction of the phase information.

Kernel-phase allows to go beyond the rules of Golay and offer better solutions for the imaging of complex sources

Martinache, 2013, in prep

http://www.frantzmartinache.com/subaru/02projects/03kerphi/01imaging/01imaging.html

Monday, May 27, 2013
The TMT ring - interferometer

492 segments
972 spatial frequencies
726 kernel-phases (75 %)
Max redundancy: 462
Mean redundancy: 124

78 segments used
972 spatial frequencies
933 kernel-phases (96 %)
Max redundancy: 26
Mean redundancy: 3

Martinache, 2012, SPIE, 8445, 04
Super-resolution imaging with an ELT: Kernel-phase interferometry

\[ I = O \otimes \text{PSF} \]

At high Strehl

\[ \Phi = \Phi_0 + A \cdot \varphi \]
Kernel or closure phase?

Low-Strehl: closure-phase wins...

Medium-Strehl: tie!

High-Strehl: kernel-phase gives another order of magnitude