KIN/PFN/LBTI heritage and lessons learned

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Why Nulling?

• Goal: Improve contrast for faint dust & companion emission very close to bright stars
  - Work inside the few $\lambda/D$ inner limit of coronagraphy

• For small stellar leaks, the “null depth”, $N$, is given by
  \[ N = \frac{I_{\text{min}}}{I_{\text{max}}} = \frac{(1-V)}{(1+V)} \]
  = ratio of the signal in the destructive & constructive interference states

• For visibilities, $V \approx 1$, i.e., $V \approx 1 - \Delta V$

\[ N \approx \Delta V/2 \quad \text{or} \quad V \approx 1-2N \]

Aim to directly measure a small number ($N$) instead of
delta from unity ($V$)
How?

- Antiphase a pair of apertures to center a dark interference fringe on a bright star
- Rotation of array (& fringes) modulates off-axis source signals

Stellar leak or null:

\[ N = \frac{\pi^2}{16} \left( \frac{\theta_{dia}}{\lambda / b} \right)^2 \]

Signals from off-axis sources:
Green: companion @ \( \frac{\lambda}{2b} \)
Blue: companion @ \( \frac{3\lambda}{2b} \)

Bracewell (1978)
What Wavelength?

• Long (MIR) wavelengths:
  • High thermal background noise
    • to see faint emission, need to remove two stronger signals:
      - star & background
  • Ground-based goal: mainly warm exozodiacal emission in the habitable zone
  • Space: detection of thermal (habitable zone) exoplanet emission

• Short (NIR) wavelengths:
  • Only need to remove one bright emission source - the star
  • But phase phase stability is much worse
  • Goal: inner hot dust (or dust scattering) & hot companions
Nulling Experiments

- BLINC/MMT etc. (Univ. of Arizona) - MIR
- Keck Interferometer Nuller (JPL) - MIR 85/4 LDLs
- Palomar Fiber Nuller (JPL) - NIR 3.2/1.5
- Large Binocular Telescope Int. (UofA) - MIR 14/8
Nulling with the Keck Interferometer

- Need to remove two different bright signals:
  - Strong (coherent) central star (few Jy)
  - Strong (incoherent & noisy) MIR background ($10^3$ Jy)

  ⇒ need two-step removal

- Nulling star requires fixed null phase

  ⇒ cannot scan null fringe

- Spatial chopping was not an option at Keck (need to use AO)

  ⇒ Use a two-stage interferometer
    - (phase chopping instead of sky chopping)

  ⇒ Need four input beams

Colavita et al.; Serabyn et al.; Mennesson et al. papers
Two stage interferometer:

• Split the two Keck apertures into 4 subapertures

• Null the star symmetrically (fixed phase):
  • Null on 2 parallel, long (85 m) baselines (~ 24 mas fringe)

• Interferometrically combine the 2 nulled outputs:
  • 4 m “cross-combiner” baseline across each aperture:
    • XC fringe spacing ~ 500 mas
  • Scan cross-combiner OPD:
    • Modulates & detects residual coherent emission
    • Incoherent background at d.c. not detected; but contributes noise

• Spatially filter the combined beams (pinhole, not SM fiber)

• Disperse & detect the 4 combined output beams:

• Subaps & pinholes define single-beam FOV: ~ 450 x 500 mas
The Null Measurement

• KIN measures the integrated intensity transmitted by the nuller fringe pattern:

\[ N = N_{\text{star}} + \frac{\int S(\theta, \phi) \, t(\theta, \phi) \, d\theta d\phi}{\int S(\theta, \phi) \, d\theta d\phi} \]

given by

\[ X_{\text{amp}}(\text{destructive nuller state}) / X_{\text{amp}}(\text{constructive nuller state}) \]

• Source model needed to estimate the total source flux

Null Measurement: Chopping between four fringe states
Stellar Null Leakage vs. Flux

\[ N = \frac{\pi^2}{16} \left( \frac{\theta_{\text{dia}}}{\lambda/b} \right)^2 \]

⇒ Both \( F_\nu \) & \( N \) are \( \propto \theta^2 \)

⇒ For a bb star of \( T > 4500\,\text{K} \) & flux density \( F_\nu \) (at \( bl=80\,\text{m} \), \( \lambda=10\,\mu\text{m} \)):

\[ N \sim 2F_\nu/T \]

- Nearby A star nulls (e.g. Vega, Fomalhaut) \( \approx 10^{-2} \)
- Nearby G2 star nulls limited theoretically to \( > 10^{-3} \)

⇒ need to calibrate with known stellar leakages (diameters)
KIN System Block Diagram

- Many λs used: MIR: nulling; K-band: fringe tracking; J/H-band: pointing

Control: Sources not bright enough at N for high-speed fringe tracking
K-band phase “fed-forward” to N-band FDL

- Keck Telescopes
- Adaptive Optics
- Dual Subaperture Modules
- Coude & Transport Optics
- Long Delay Lines
- Wavefront Sensor

- N-band FDLs
- N-band ADCs
- Quasistatic H2O dispersion
- N-band fringe phase
- N-band fringe phase

- Beam Compressors
- Intensity Correction
- Tip-tilt Correction
- Dispersion Correction
- Nulling Beamcombiners
- Spatial Choppers
- Cross-Combiners

- K-band Beam-combiners

- FATCAT: K-band Fringe Tracking Camera
- KAT: J-band Angle Tracking Camera

Metrology
Sidereal Target

Quasi-stationary sources not bright enough at N for high-speed fringe tracking
K-band phase “fed-forward” to N-band FDL
KIN Results

- 47 nearby stars surveyed for exozodi @ 8.5 microns
- Final best calibrated null ~ 0.2 – 0.3%
  (Milan-Gabet et al. 2012; Mennesson et al. 2014)
- Upper limits are of order a few hundred zodis
Conclusions & Lessons Learned from the KIN

• Beam geometry:
  • Single aperture beam small
  • Fringe pattern: null fringe too narrow (too much stellar leak)
  • Long baseline fringes too narrow (integrate over many fringes)
  • Limited baseline rotation capability (Earth rotation)

• Beamtrain:
  • High beam emissivity & low transmission,
  • Residual beam shear between sub-aps
  • Coherent background beam emissivity (coherent emissivity crosstalk)
  • H₂O residual dispersion in unbalanced atmospheric paths → nulls vary across passband

• Four beams used instead of two:
  • Optomechanical complexity
  • Operational complexity – few people could run it
A Rotating-Baseline Nuller, a la Bracewell/TPF-I: The Palomar Fiber Nuller

- Generate one (or more) baselines between sub-apertures on a large telescope
  - Rotate the baseline(s) to modulate the signals from off-axis sources (via K mirror)
  - Small IWA (< \( \lambda/D \)) provides a very unique coronagraphic IWA
- Uses the facility ExAO system as the first-level fringe tracker (no delay lines needed)

\[
\text{IWA} \sim \frac{\lambda}{4b} = \frac{\lambda}{4(D-d)} \rightarrow \frac{1}{4} \frac{\lambda}{D} \\
\text{OWA}_{\text{SM}} \sim \frac{\lambda}{2d} \rightarrow \frac{D}{2d} \left( \frac{\lambda}{D} \right) \rightarrow \frac{5}{3} \left( \frac{\lambda}{D} \right) @ \text{Palomar}
\]

Operates entirely inside normal coronographic IWA

<table>
<thead>
<tr>
<th>System</th>
<th>IWA (mas)</th>
<th>( \lambda/D )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Palomar</td>
<td>33</td>
<td>90</td>
</tr>
<tr>
<td>Keck</td>
<td>13</td>
<td>45</td>
</tr>
<tr>
<td>TMT</td>
<td>4</td>
<td>14</td>
</tr>
</tbody>
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Why: small inner working angle
The Palomar Fiber Nuller (PFN)

Serabyn, Mennesson, Martin, Liewer, Loya, Hanot, Kuhn

• **Palomar ExAO**: stabilizes OPD (~200 – 250 nm rms)
• **Split mirror**: OPD scans and fine OPD matching
• **Pupil Mask**: two elliptical holes on primary image
• **Pupil shear**: match beam intensities
• **K-mirror**: baseline rotation
• **Choppier wheel**: rapid calibration
• **Dispersion correction**: increased injection and BW
• **IR SM fiber combiner**

Mennesson et al., Serabyn et al., Martin et al.
Keeping it Simple: Single-Mode Fiber Combiner

Behind ExAO system →
- Fiber coupling very stable:
- Fringes very stable

Single-beam coupling stable

Focal plane intensity

Single-mode fiber

Common focusing optic (OAP)

Beam 1

Beam 2

SAP

PSF

SM

$(E_1 - E_2)^2$

$E_1 - E_2$

Slow scan:
$\alpha$ Her

Interferometric Signal

Time in s

0 5 10 15 20

0 1 2 3 4 5

0 0.2 0.4 0.6 0.8

Time in s

0 20 40 60

0 0.2 0.4 0.6
Null depth not super-stable

- Stabilize only well enough to stay near the right fringe minimum with ExAO
  - ExAO allows a larger amount of time to be spent near null
  - Can enable $\sim 10^{-4}$ null depth meas. on very bright stars

Null depth seen in raw fringe scan via flat fringe minima
But, N not given by “mean null level”

Stellar diameter measurement:

Model one baseline rotation with K-band nuller

ExAO OPD correction

10^{-3} contrast binary

Null depth seen in raw fringe scan via flat fringe minima
But, N not given by “mean null level”
Measurement of Null Depth from Statistics of the Null: The Null Self-Calibration Algorithm

- One-sided fluctuations near null because $N \propto \varphi^2$
  - Can invert null depth fluctuations
    - Analytically in simple cases
  - $p(N)dn = p(\varphi)d\varphi$; assume Gaussian fluctuations
    - Use statistics in reality
  - Model null distribution to recover astrophysical null
- Relaxes stabilization requirements significantly
  - Enables nulling at shorter wavelengths
  - Analogous to dark speckle techniques

$\beta$ Peg; K-band

Hanot et al. 2011
Accuracy Improvement with Null Self-Calibration

NSC yields an order of magnitude Improvement in null depth accuracy!
Stellar Measurements with the PFN’s 3.2 m baseline

• High accuracy (a few 0.01 % to 0.1%) has enabled measurements of stellar diameter and binary separation with a very short baseline!

• A bigger telescope & baseline would help!

This is what TPF-I/Darwin aimed at doing!
PFN Dust Observations

• **AB Aur:**
  Herbig Ae/Be pre-main sequence star  
Mass: 1.5-10 $M_{\text{sun}}$  
Age: 1-4 MYr  
Dist: 144 pc

![AB Aur - Subaru](image)

Kuhn et al.

Bright inner dust: Inner spiral or companion?

• **Vega:** shortest baseline obs., but deepest limits (Mennesson et al. 2011)

![Vega - Subaru](image)

• **Hot inner dust sources:** Mini-survey carried out of Absil detections (~ 10 stars): detection limits of N ~ 0.2%  
  - Preliminary conclusion is that 2 micron dust is at small radii (in preparation)
The Palomar Fiber Nuller: Performance & Limitations

• High-accuracy NIR nulling \( (N \sim \text{few } 10^{-4} \text{ to } 10^{-3} \text{ or so at } K_s) \) enabled by:
  • Lower background than MIR
  • Use of ExAO as cross-aperture fringe tracker
  • SM fiber for WF error term removal
  • Rapid null-depth calibration
  • Null self-calibration algorithm

• Limitations to PFN:
  • Baseline a bit too short
  • Null fringe too broad to see very close in
  • Phase stability is relaxed, but need to make sure that one is on correct fringe
  • Atmospheric refraction for non-horizontal baselines
  • Atmospheric dispersion
  • Integration time a bit too long (> 5 msec to date)

• A nuller on a larger single-aperture telescope could be interesting (esp. TMT/ELT)
LBTI Nulling
Hinz et al., several

• Beam train limitations largely removed:
  • Emissivity much lower
  • No correlated coherent emissivity from optics
  • Shear much easier to deal with, with a pair of round beams

• Greatly reduced H₂O dispersion:
  • common mount
  • horizontal baseline

• Using nulling self-calibration

• Spatial filtering not used
The LBTI MIR Nuller

(Defrere et al. 2016)

Phase jitter $\sim 0.2\text{ rad}$
The LBTI Beamcombiner and Fringes

simple & cold

(Defrere et al. 2016)
Background removal with spatial nodding/chopping

- Background >> star
- Need to remove background to a few ppm
- Need to null to a few $10^{-4}$ to get to tens of zodi range
Null Self-Calibration employed for LBTI data reduction

Defrere et al. (2016)
Mennesson et al. (2016)
High Nulling Data Quality

$\eta$ Crv
Defrere et al. (2016)
Performance History and Goals

Danchi et al. 2016
LBTI Nulling

• Nulls to $5 \times 10^{-4}$ @ 11 microns
  - Almost 10x better than Keck
    • 10x lower background
    • Null self-calibration

• Limitations:
  • Background and background bias fluctuations between on & off beams
    • Background varies spatially & temporally
    • Nod period of ~ once per minute too slow
  • Fringe pattern – broad null fringe
Overall Lessons Learned

• Minimize complexity
• Low emissivity extremely important in the MIR
  • (order of magnitude lower at LBTI)
• Non-interferometric solutions for background removal good
• $b/D$ can be very constraining on a single baseline
  • Long baselines $\rightarrow$ high stellar leak
  • Short baselines $\rightarrow$ can’t get close to center
  • (TPF/Darwin solved this (on paper) with multiple baselines)
• Nulling self-calibration has enabled high accuracy nulling in both the NIR & MIR
  • Dispersed nulling and very rapid readout would help get the most out of NSC
• There is still great potential for high-accuracy NIR nulling/visibility measurements