Accessing small inner working angles with a rotatng sub-aperture nuller on a single-aperture telescope

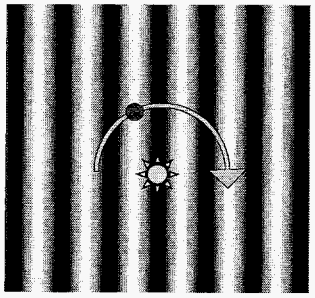
Gene Serabyn

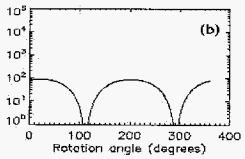
Nice IAU meeting

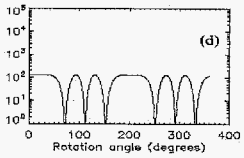
October 2005

Space-Based Nulling Interferometry

- Phase a pair of telescopes to center a dark interference fringe on a bright star
- Rotate array to modulate off-axis signals by means of rotating transmission pattern







What gets measured by a rotating nuller?

- Fixed phase relationships between apertures implies no quadrature information.

⇒ Complex source visibilities cannot be measured on fixed-phase nulling baselines

⇒Usual complex Fourier transform relationship (visibilities to image) not available

- Signal: $S(\alpha(t),\lambda) = \sum I(\theta,\psi)\, T_{fr}(\alpha(t),\lambda,\theta,\psi,\varphi)$
- Reconstruction by e.g., cross-correlation:

$$I(\theta,\psi) = \sum S(\alpha(t),\lambda)\, T_{fr}(\alpha(t),\lambda,\theta,\psi,\varphi)$$

- Extreme solution is to deploy an array of nullers, and measure visibilities between them

Example: Single Baseline, Single Planet

- The transmission of the planetary signal as the fringes rotate with the baseline is given by

$$T(x,t) = \sin^2(x/2) = (1-\cos(x))/2$$

where $x = k\mathbf{b}\bullet\theta = kb\theta\cos(\alpha(t))$

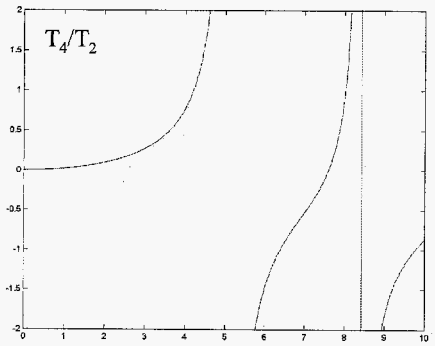
So

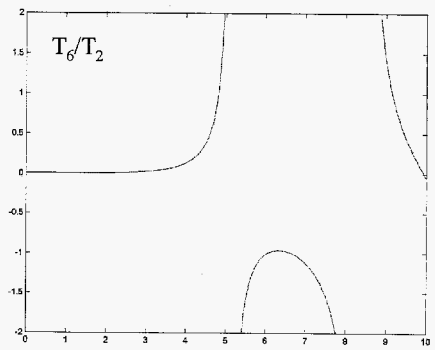
$$T(x,t) = (1-J_0(x))/2 - {}_1\Sigma^{\infty}\, J_{2n}(x)\cos(n\varphi(t))$$

- For planets inside of the first fringe maximum, signal mostly in 2nd harmonic, as is exozodi.
- As θ_{planet} increases, higher harmonics generated.

Harmonics in the Planetary Response

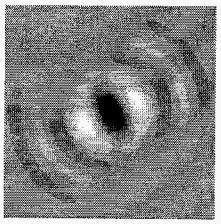
- $T_4(x)/T_2(x) = J_4(x)/J_2(x)$
  = 0.206 at 1st fringe max (at $x = \pi$ on the plots)
  = 0.1 at .697 of 1st fringe max
- How does this translate into detectability?



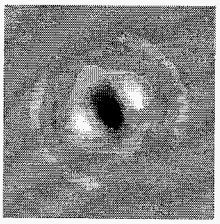


Imaging inside the first maximum

Reconstructed "Images". Cross Correlation method.
Single Bracewell baseline B. No Noise added. 6–20 microns

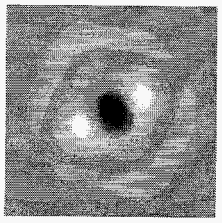


Planet at 0.5* λ/2B
at λ=10 microns

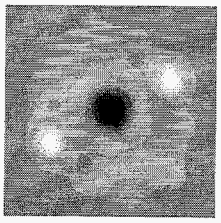


0.7 * λ/2B

- Detected position tracks planet in to 0.8-0.9 λ/2b



λ/2B



λ/B

3λ/B

Reconstruction Issues for TPF/Darwin

- Define inner working distance (IWD) for given configuration/algorithm for single planets
- Understand effect of multiple planets on detectability & IWD
- Understand impact of extended exozodiacal light
- Investigate alternative data reconstruction algorithms
- Select optimal configuration and baseline scales
- Demonstrate that the approach is robust

- To a large extent, the viability of TPF-I depends on the robustness of the signal extraction
- Wouldn't it be nice to test this from the ground?

Starting Point

- Test the idea of planet detection/modulation with a ground-based rotating interferomer
- The approach:
  - Generate one or more baselines between different sub-apertures on single, large telescope.
  - Rotate the baseline(s) to modulate the signals from off-axis sources
  - Keep it simple to demonstrate basic physics

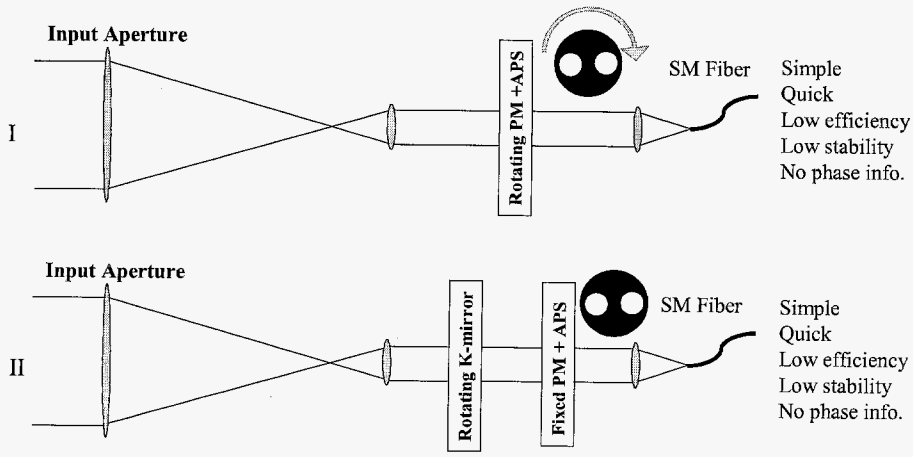
A rotating baseline on a single-aperture telescope

- What is needed?

  Telescope
  1-Baseline Generator
  2-Baseline Rotator
  3-Nulling Beam Combiner
  (with field reversal element)
  4-Single Mode Filter
  5-Detector

- Simplest start-up approach might be to use a fiber beam combiner and to operate narrowband at first

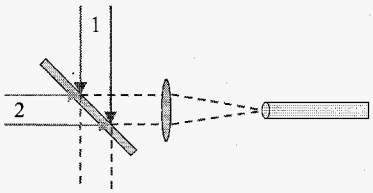
Potential Layouts: I & II



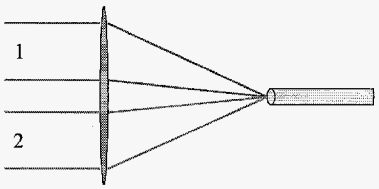
PM = Pupil Mask
APS = Achromatic Phase shifter

The Idea

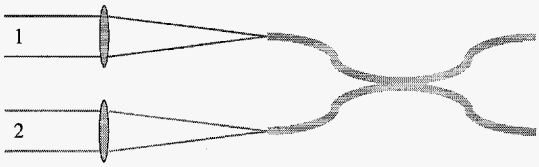
- Combine beams in a fiber instead of at a beamsplitter



A: Combine two free-space fields
(fiber acts as a spatial filter)

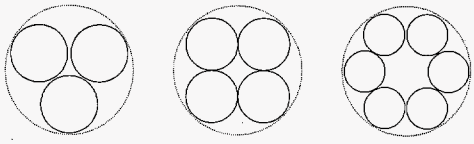


B: Combine free space fields via coupling to fiber mode
(can combine n beams)



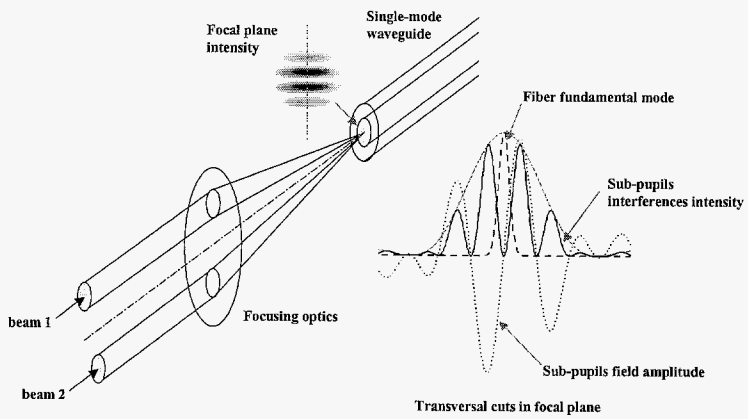
C: Combine fiber fields via fiber or waveguide cross-coupler

Multi-axial single-mode beam recombination

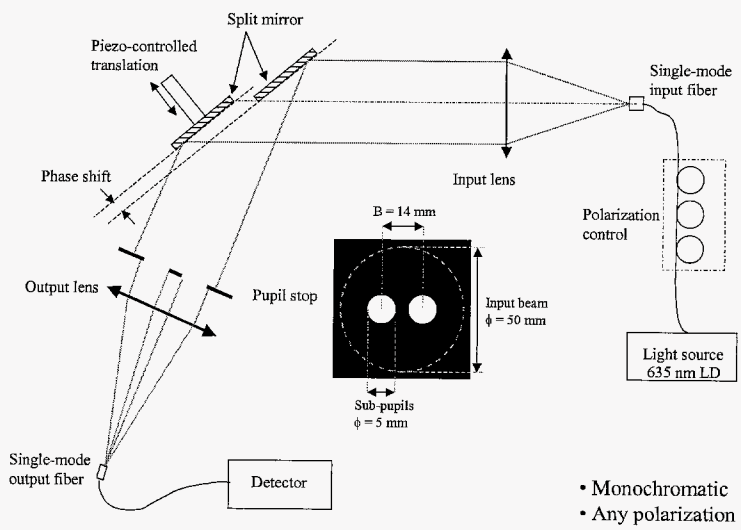


- Wallner et al. & Karlsson et al. in Glasgow SPIE (2004)

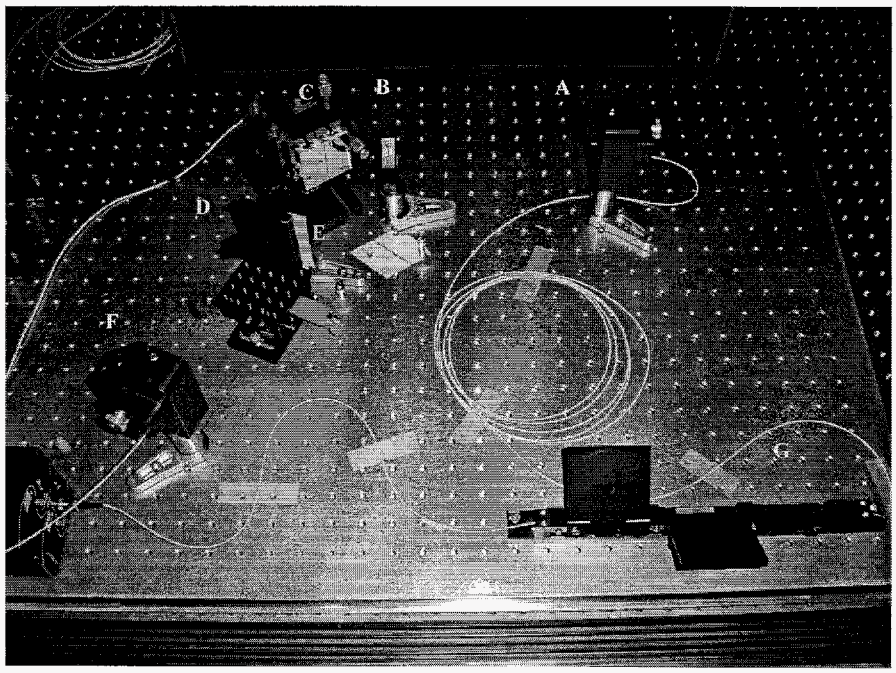
The Fiber Combiner



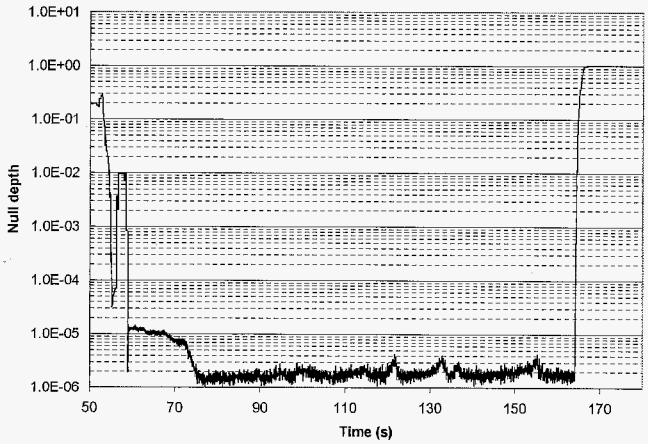
Experiment Layout



- Monochromatic
- Any polarization



Results



- Visible laser
- Random polz'n.

- Best measured visible laser null (few second average): 1.3×10^{-6}

⇒ Basic physical principle of fiber nulling demonstrated

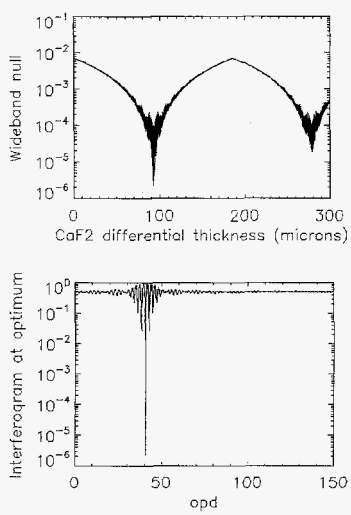
- Next (unfunded) steps: broadband, infrared, telescope trials

Achromatic Phase Shifter

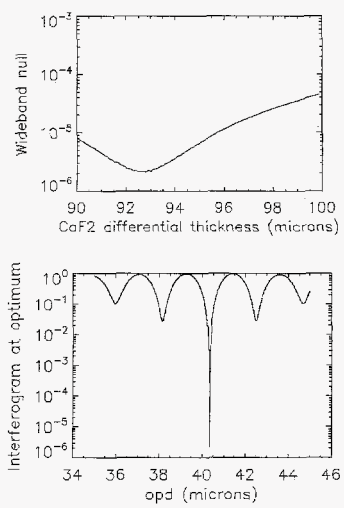
- CaF2 solution studied. Best solution is to use 2 windows with specified different thicknesses, or a 4 wedge device (id. Keck).
- Differential rotation solution is bad (best K-band N=6e-3, because of chromatic Δg?).
- Assuming top-hat 2 to 2.4 micron band, a null of 2.2e-6 is theoretically achievable, for a differential glass thickness of ~93 μm and an additional opd in air of ~40.3 μm
- N=1e-5 (resp. 1e-3) requires opd rms < 2.2 nm (resp. 22 nm)
- Differential thickness is 93+/-3 micron to guarantee N<1e-5. Can be adjusted by mounting 2 windows of relatively well known Δg and rotating them by a few degrees (?)

APS device

- Best wide band null vs Δg:



Tolerance on Δg:

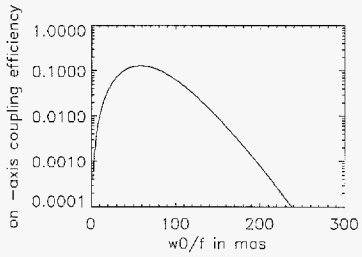


Notation

b= interferometric baseline in m. (Palomar: B=3.5m)
d=sub-aperture diameter (Palomar D=1.5m)
λ=observing wavelength (nominally 2.2 microns)
w_0: fiber field mode radius at 1/e attenuation
a: fiber core radius (a~w0 close to cut-off wavelength)
f: focal length of injection length into fiber

Detection: SM fiber injection and specs

- Assuming a b/d ratio of 3.5/1.5, optimum injection of an on-axis source in *constructive mode* occurs for $w_0/f = 0.19\ \lambda/d$ (= $0.45\ \lambda/b$)



Max=0.128

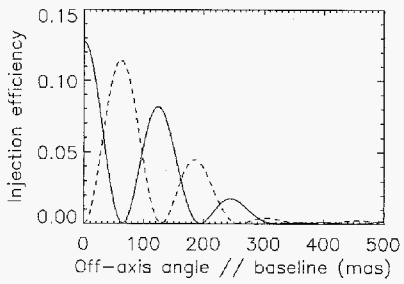
(without Fresnel losses)

- Since the final lens diameter ϕ is > b+d=(10/3)d, one gets for the final lens f-ratio:
  $f/\phi < 1.58\ (wo/\lambda)$, i.e.
  $f/\phi < 3.0$ for w_0~a=4.25 microns and λ=2.2 microns

- In order to ease the injection into the fiber, one wants a core radius as large as possible, i.e. work at λ_c ~ 1.90-1.95 micron, and a small NA (<0.15).

Off-axis source injection

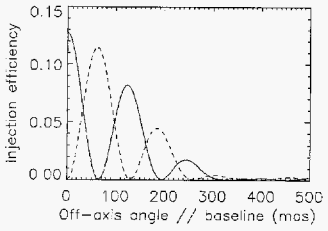
- Assuming b/d= 3.5/1.5

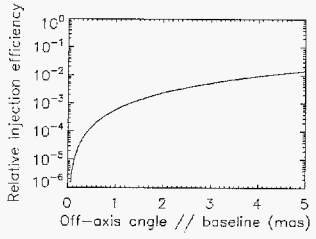


Injection efficiency as a function of off-axis angle in the baseline direction, at optimum w0/f

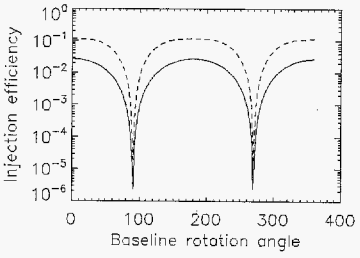
Off-axis sources

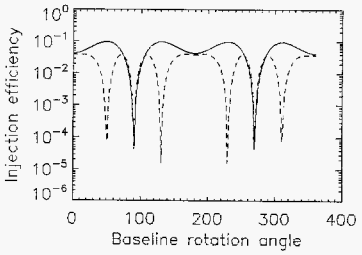
- Injection efficiency
  (b/d=3.5/1.5, no pupil densification)



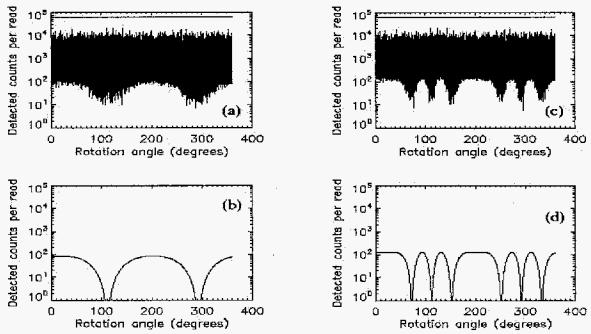


Modulated signal (sources at 20, 60, 100 and 200 mas)

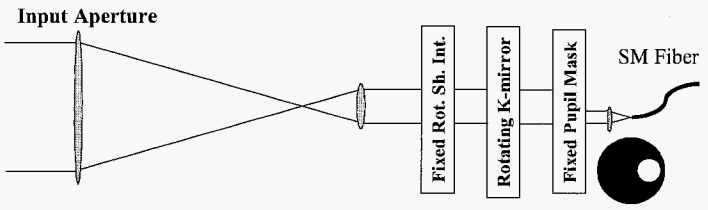




Expected Performance with no extra Phase Control



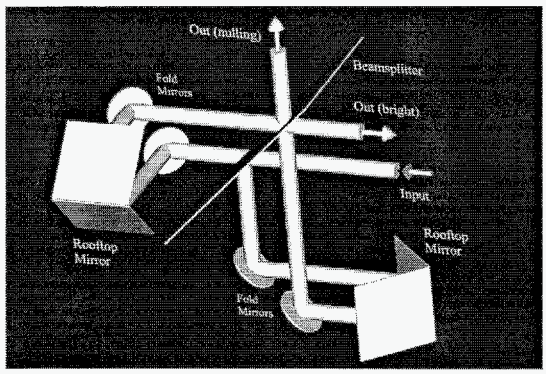
Potential Layouts III

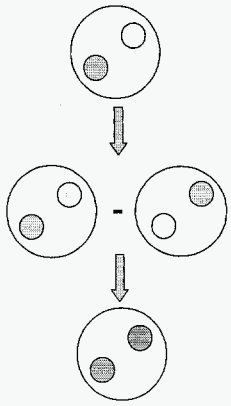


More complex
Higher efficiency
Phase control
Stability
No phase plates
More complex
More costly

Symmetric Rotational Shearing Interferometer

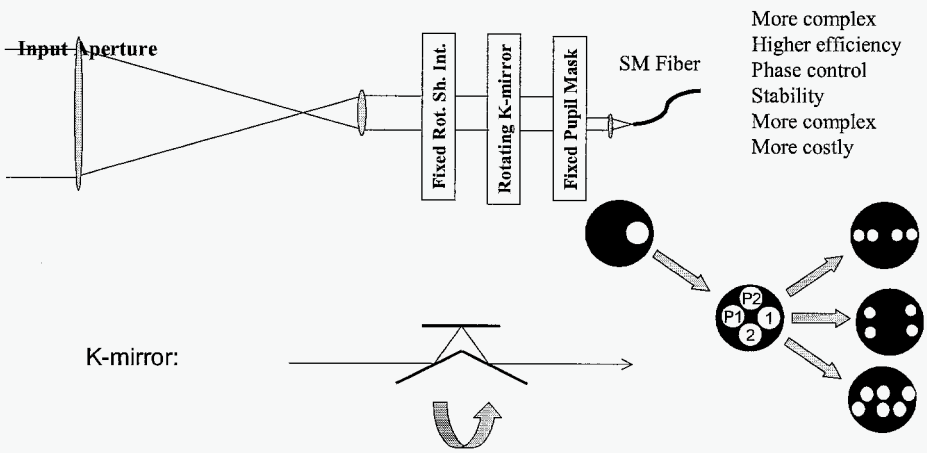
- Perfectly symmetric recombination
- Provides relative field flip
- Generates all symmetric baselines across the center of the aperture in the recombined beam
- Only need to select a single subpupil to define a baseline





Ren & Serabyn (AO, in press)

Full-up Layout



- RSI provides two duplicate copies of every baseline
- Use one copy for phase sensing (AO will provide ≈ 100-200 nm of phase)
- Only need average phase between large subapertures ⇒ lots of signal
- Use first subaperture to phase second subaperture for good null
- Rotating K-mirror rotates the recombined aperture prior to the sub-pupil stop
- Can go to many simultaneous subapertures and/or baselines

Wavelength of operation

(b/d=3.5/1.5)

- mK=5 star (2 x 1.5m aperture):

~1e6 ph/s in K, ~1e6 ph/s in L'

- 300K Thermal background per λ^2:

1.3 e3 ph/s in K, 4.4 e6 ph/s in L'

- Current detector NEP equivalent photon count:

4.9 e9 ph/s in K, 8.2 e9 ph/s in L' (both at 200kHz)

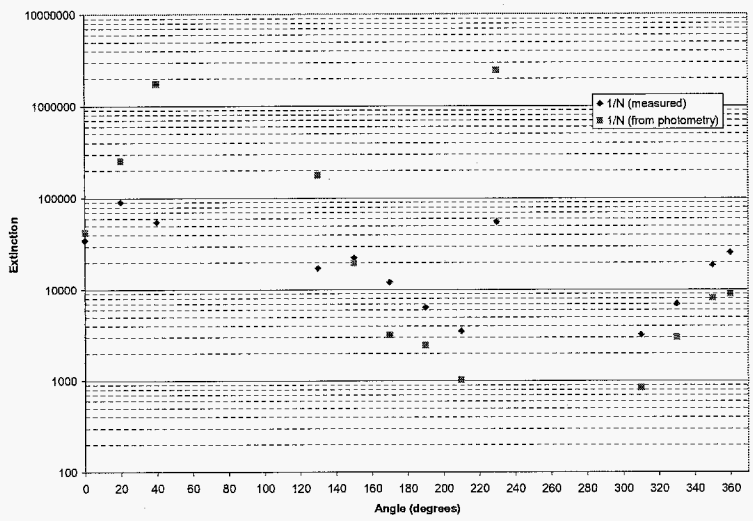
Current NEP unacceptable on the sky in L'

K band much better (8 stellar mag gain!)

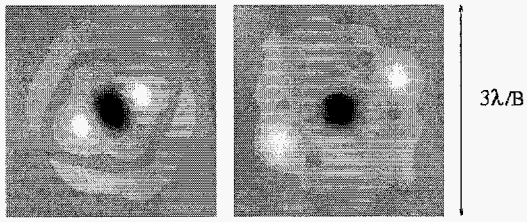
TBD for sky experiment

- Compute signal/modulation from off-axis source (done)
- K/L' trade-off (quasi done), so now H/K trade-off
- IR camera /single pixel photometer trade off
- APS or not
- APS ghost pb: wedged windows (2 ') with rotating K mirror, or AR coated high quality windows with rotating mask?
- Performance analysis/simulation, including realistic opd spectra and noise levels
- Define location of the nuller

Initial Rotation Trial



Coronagraphic Properties and Conclusion



- Detected position tracks planet in to 0.8-0.9 λ/2b
- At Palomar, λ/2b = 60 mas for λ=2 μm and b=3.5 m

- Let b/D = ¾, so λ/2b = 2/3 λ/D
  ⇒ Companion detections possible inside of λ/D with this approach (with good AO correction)

⇒ The rotating baseline approach envisioned for space-based nullers can be tested on the ground with a technique that also provides very good coronagraphic capability