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Planet Detection and Spectroscopy in Visible Light with a Single Aperture Telescope and a Nulling Coronagraph

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Abstract: **This talk describes a new concept for visible direct detection of Earth like extrasolar planets using a nulling coronagraph instrument behind a 4m telescope in space. In the baseline design, a 4 beam nulling interferometer is synthesized from the telescope pupil, producing a very deep θ^4 null which is then filtered by a coherent array of single mode fibers to suppress the residual scattered light. With perfect optics, the stellar leakage is less than 10^{-11} of the starlight at the location of the planet. With diffraction limited telescope optics (lambda/20) ,suppression of the starlight to ~1e-10 is possible. The concept is described along with the key advantages over more traditional approaches such as apodized aperture telescopes and Lyot type coronagraphs.**

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Planet Detection with a Nulling Interferometer

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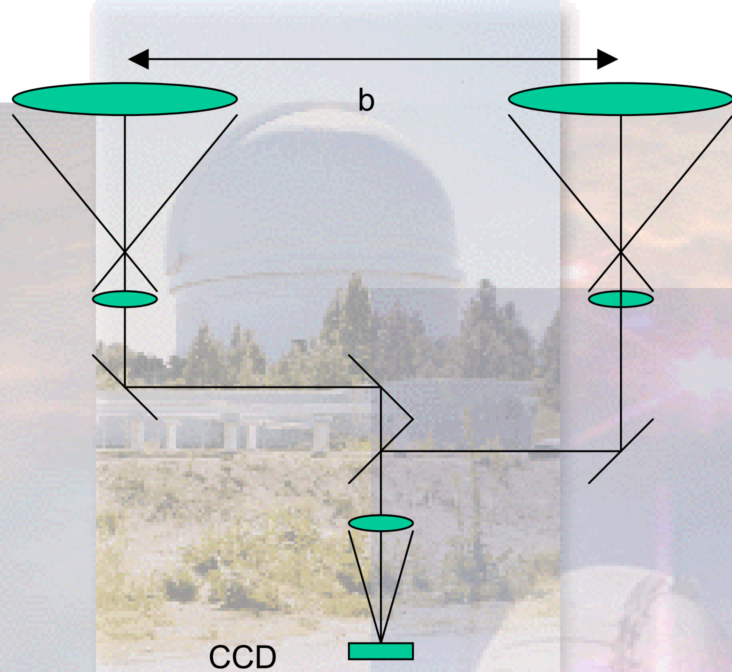
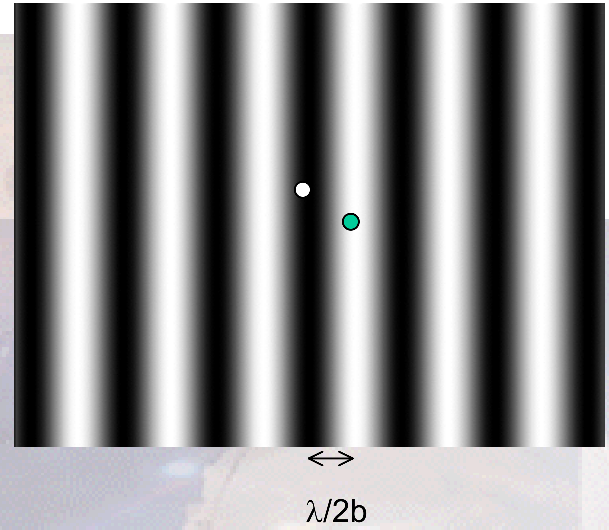




Transmission Pattern of Nuller
On the sky. (Star is at the center)

•When the light from two pupils are combined, the output can be imaged.

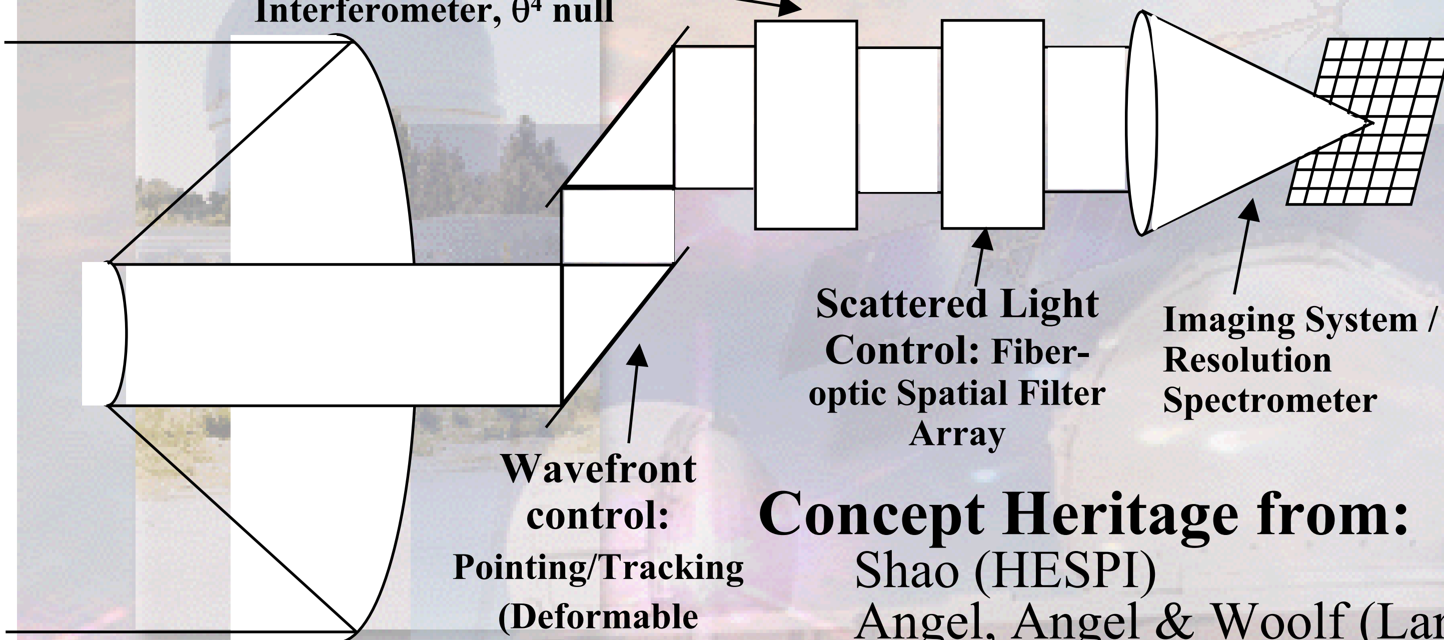
•The image is an Airy function with diameter 2.44l/D where D is the telescope diameter.

•But the intensity of that image is modulated by the fringe pattern (on the sky) where b is the baseline between the pupils.

- •if the star is at a null, the star's image has 0 intensity. If the planet is at the peak, the planet's light is unattenuated.

•A nulling interferometer that works with a single aperture telescope is different than one that combines light from 2+ telescopes

Visible Nulling Coronagraph Concept

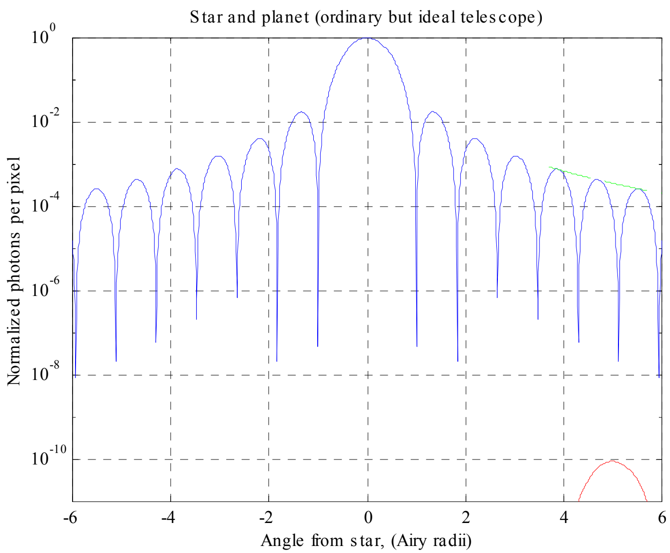


Concept Heritage from:

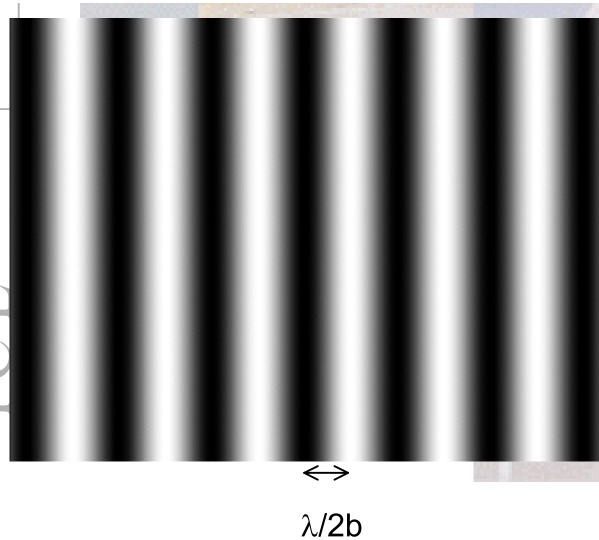
Shao (HESPI)
Angel, Angel & Woolf (Large Telescopes, Nulling Interferometers)

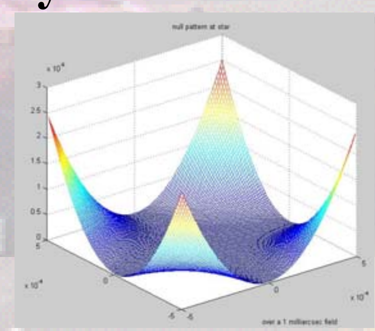
The Nulling Interferometer is the <u>Enabling</u> Technology
The Fiber-optic Spatial Filter is Enhancing Technology

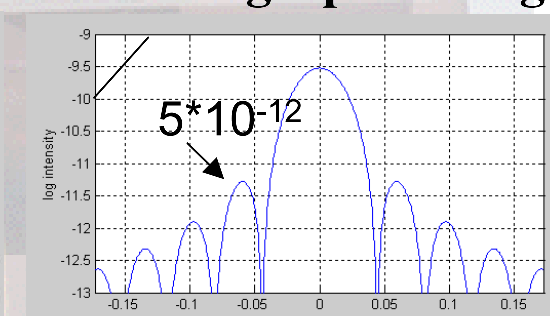
Comparison of a Single Aperture Telescope and Visible Nulling Interferometer to a Coronagraph



- A modest sized aperture telescope can theoretically resolve an extra-solar planet
  - Jupiters at 10 pc $b > 0.15$m (λ=0.75μm)
  - Earths at 10 pc $b > 0.75$ m
- The major technical issue is overcoming the contrast between star and planet (10^{-9}-10^{-10})
- Conventional coronagraphs need to perform detection at 3rd Airy ring or greater to suppress the contrast ratio
- A Sun at 10pc is 1 mas in diameter. Total leakage because of the nuller is < 10^{-9} (Not yet considered for coronagraphic imaging).







- A nulling interferometer can perform this detection within, $\theta = \lambda/2b$, $b \ll D$ *[(O)~4m for TPF Earth at 10pc]*

Critical Comparison of a Visible Nulling Nuller Interferometer to a Coronagraph

Attribute	Coronagraph	Nulling Interferometer
Telescope Design	Imaging mode	Beam Compression Cassegrain Configuration Acceptable
Telescope Primary Mirror	'Hubble' (λ/80 rms) or better minimum power in midspatial frequencies	Diffraction Limited (λ/20 rms OK)
Configuration	Unobscured configuration Required	Cassegrain acceptable, Unobscured configuration acceptable
Diffraction Control		
Diffraction Suppression Technique	Occulter and Lyot Mask: Localization, Size, Apodization critical	θ^4 null required in nulling interferometer, O(Å) Path length control for nulling and to suppress stellar leakage
Pass band	na	Dispersion correction critical for wide band nulling
Diffraction Suppression	3 Airy Rings (10^{-9}), 4 Airy Rings (10^{-10})	2 Airy Rings (10^{-11})
Scattered Light Control		
Wavefront Sensor O(Å) sensitivity to drive deformable mirror to suppress mid-spatial frequency errors	(~1300s for m_v = 5 star)	(~80s for m_v = 5 star)
Pointing and Tracking	~1mas	~1mas
Deformable Mirror	Å resolution over O(4000) actuators, amplitude and phase control	Å resolution over O(3000) actuators, amplitude and phase control, tip/tilt and piston control
Spatial Filter Array	na	O(300-1000) Diffraction Limited Coherent Array Required (λ/10 rms)
Demonstrated Scattered Light Supression	$>10^{-6}$ per Airy spot	7×10^{-9} sustained per Airy spot 6×10^{-10} transient per Airy spot

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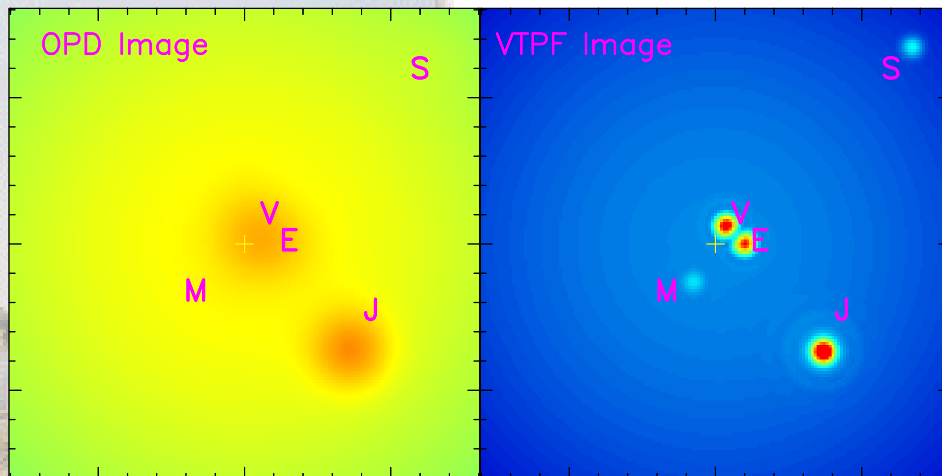
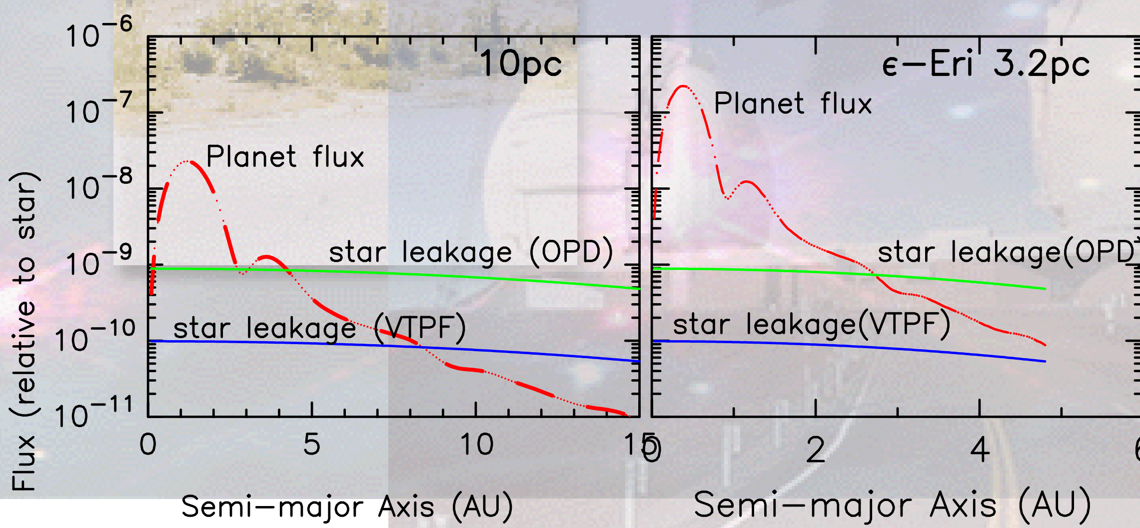
Imaging Capability

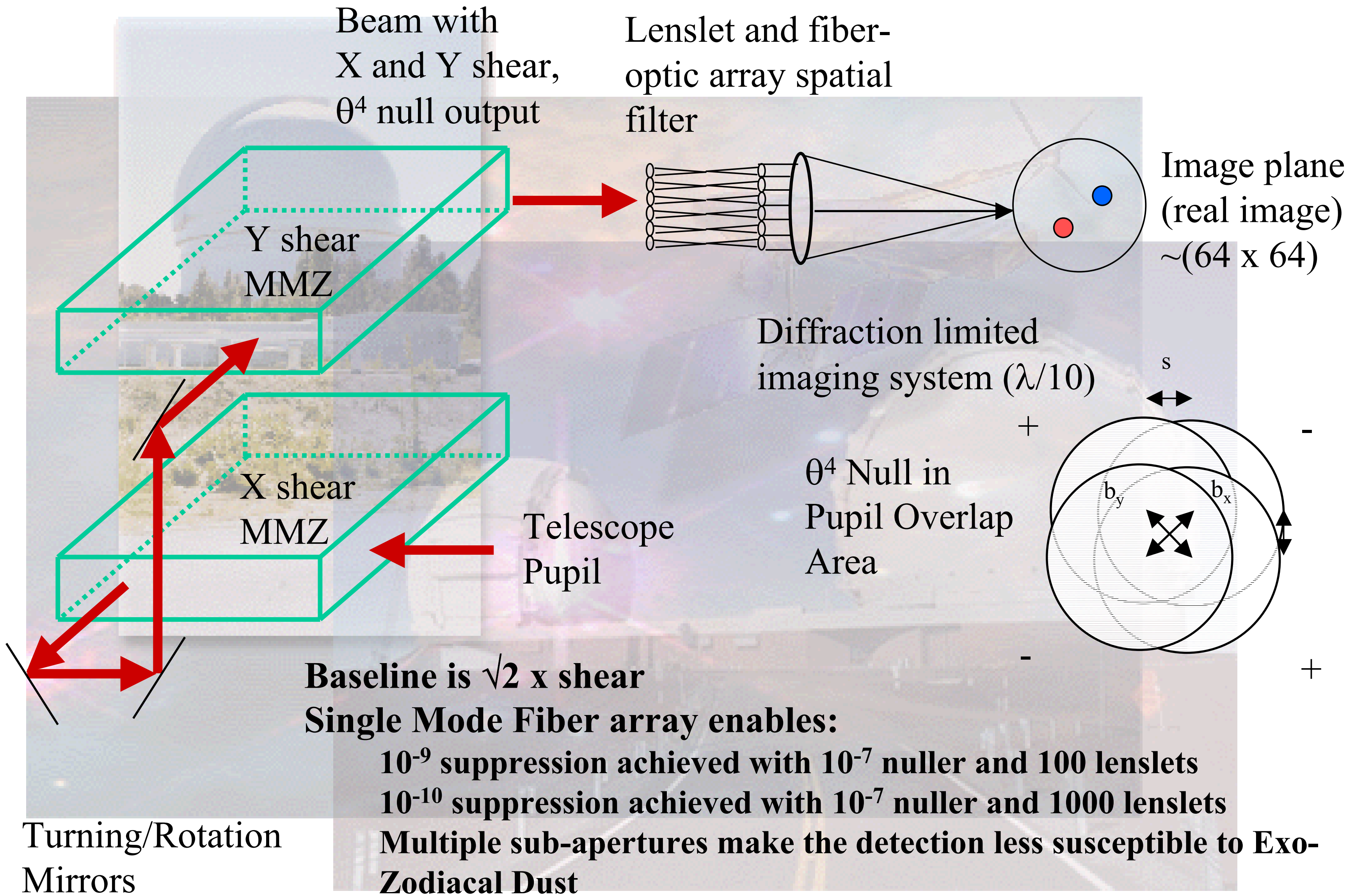


(left) Simulation of solar system with 1.5m aperture. (right) Simulation using a 4m aperture. The brightest emissions are red.



Simulations of observed planet fluxes compared to the PSF of the stellar leak as a function of the planet distance. The planet flux densities are assumed to be that for Jupiter size and given in units of stellar flux. Null depth of 10^{-7} was assumed, and the planet fluxes are averaged over all orientations of the null pattern.

Visible Nulling System Concept



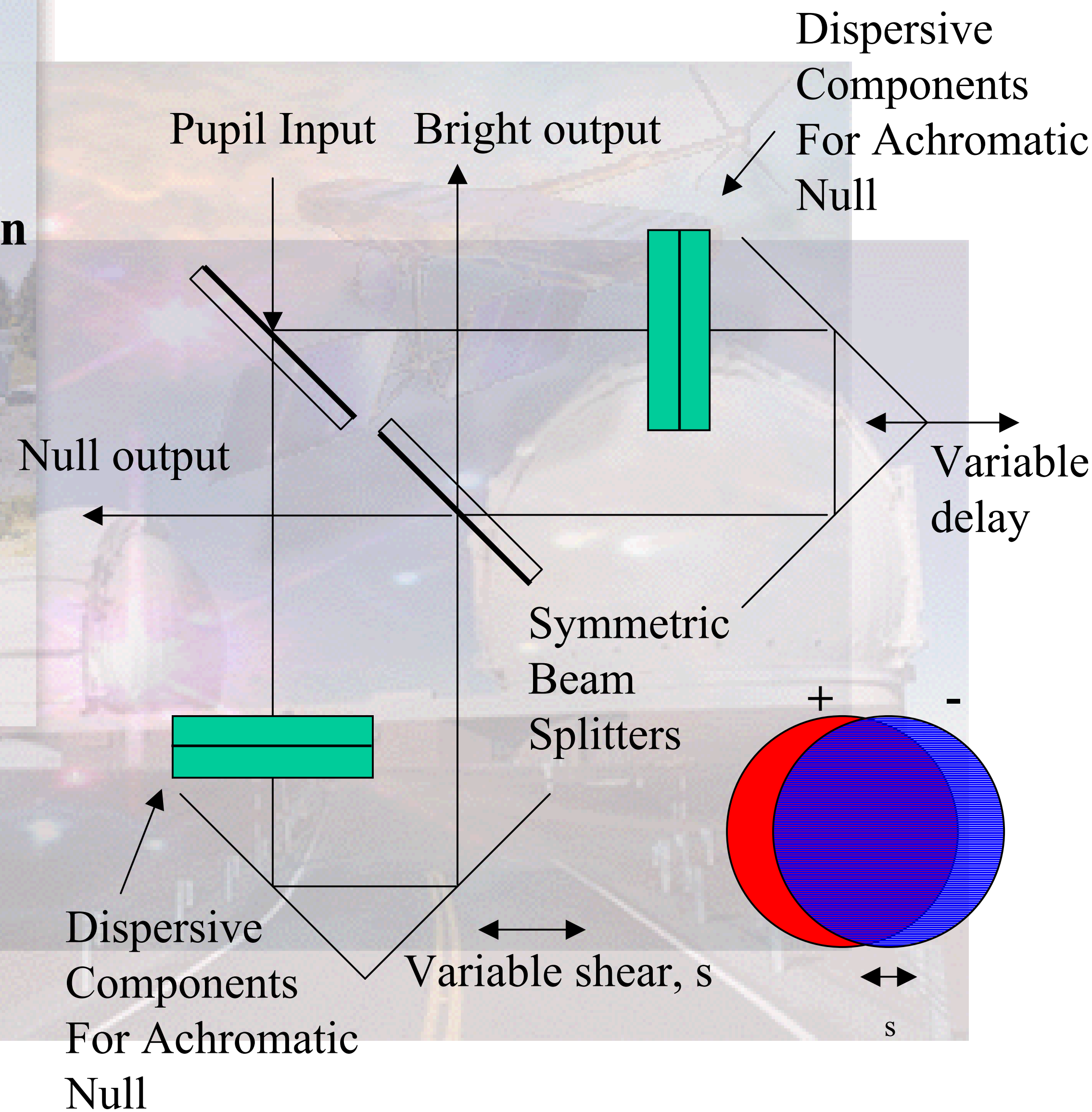
Baseline is √2 x shear

Single Mode Fiber array enables:

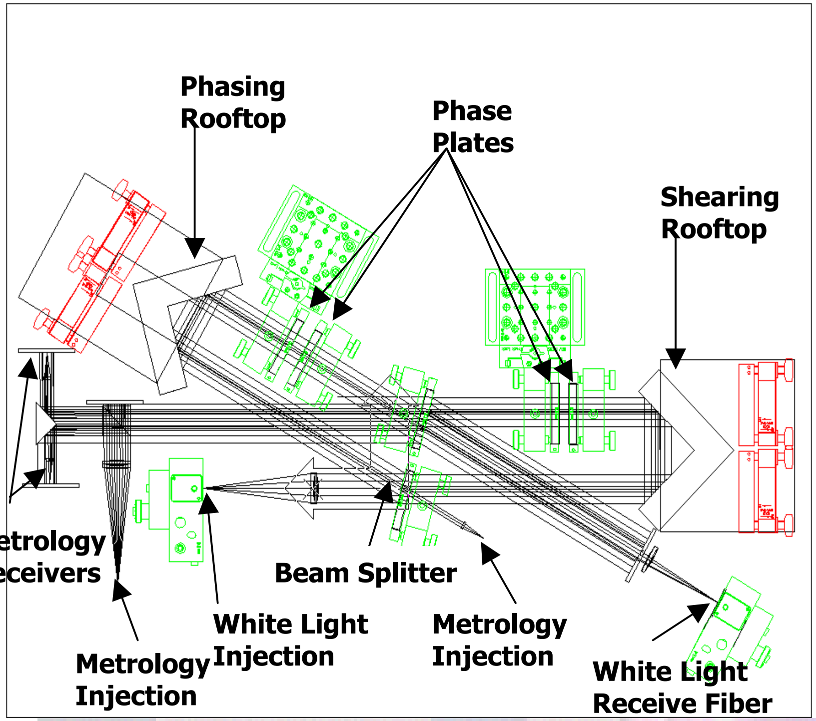
- **10^{-9} suppression achieved with 10^{-7} nuller and 100 lenslets**
- **10^{-10} suppression achieved with 10^{-7} nuller and 1000 lenslets**
- **Multiple sub-apertures make the detection less susceptible to Exo-Zodiacal Dust**
  - **Residual background is incoherent with planet image**
  - **Preserves field of view**

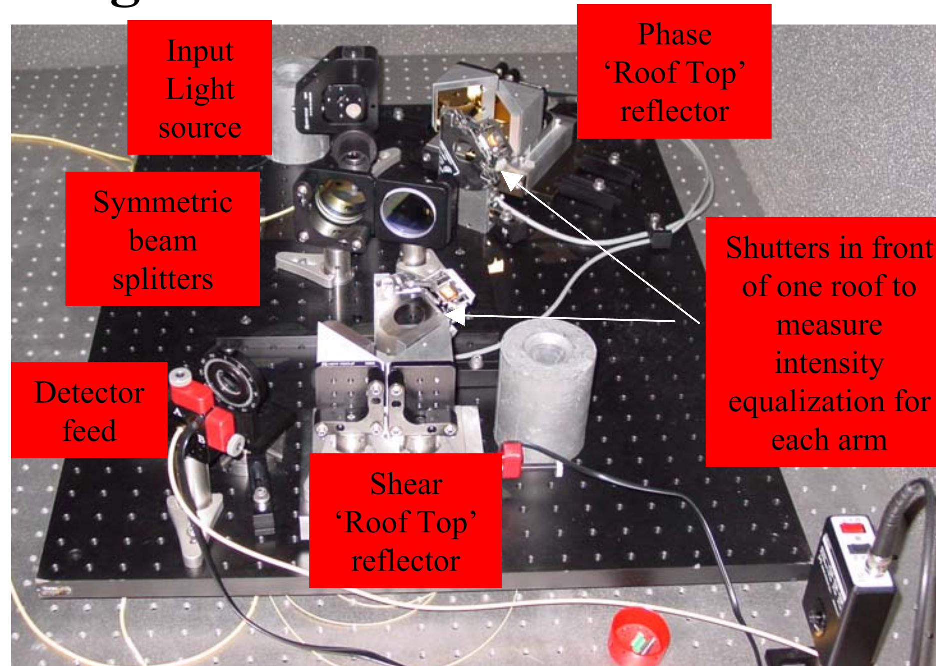
Achromatic Nulling Interferometer Demonstration

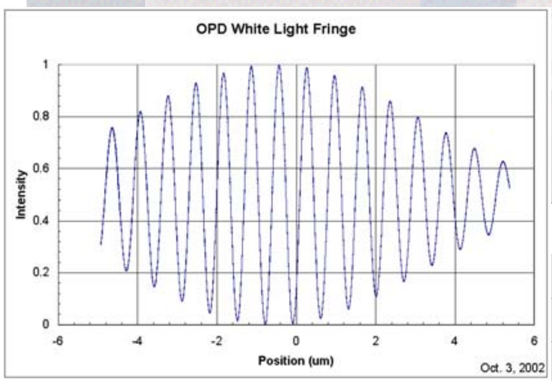
- **Single pupil input**
- **Symmetric design**
- **Preserves pupil orientation and polarization**
- **Pupil shear adjustable– variable null baseline**
- **Dielectric plates provide achromatic null**

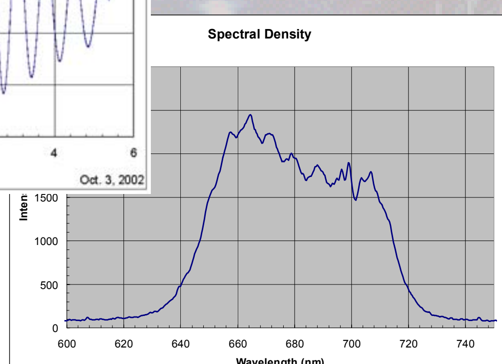


Proof of Concept Nulling Interferometer



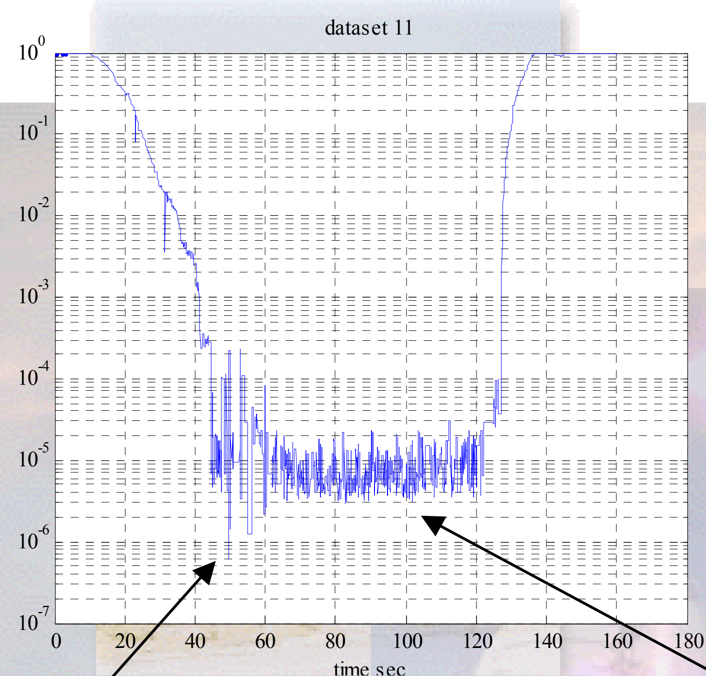




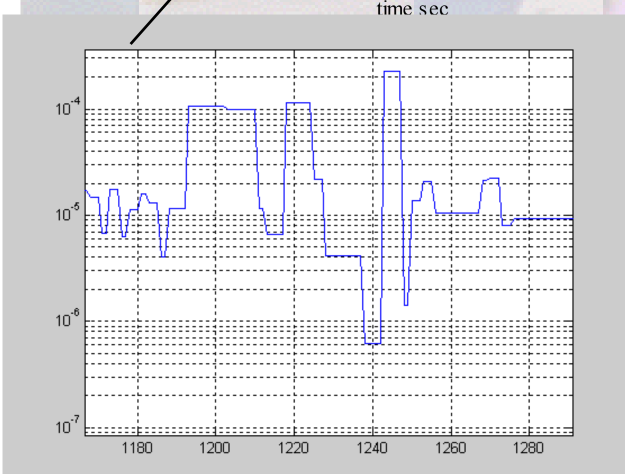


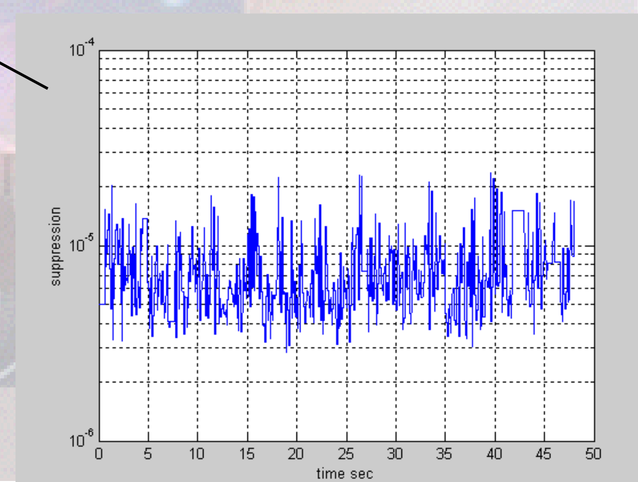
- **First Laboratory Results--White Light Fringe Scan**
  - Optical bench 'isolated' with pads and doors, otherwise ambient laboratory conditions

Deep Nulls from Monochromatic Light



- Laser diode source ~1nm bw
- Intensity matched to 0.1~0.2%
- Polarization aligned
- Small dither imposed, sync'd with scope display. Dither signal demodulated by "eye"
- OPD control by hand on pzt voltage knob.
- Closed loop control currently being integrated





- Best transient null 6e-7, 40msec sampling

- Sustained null, Average leakage 7.6e-6

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Coherent Fiber Array Nulling Requirements

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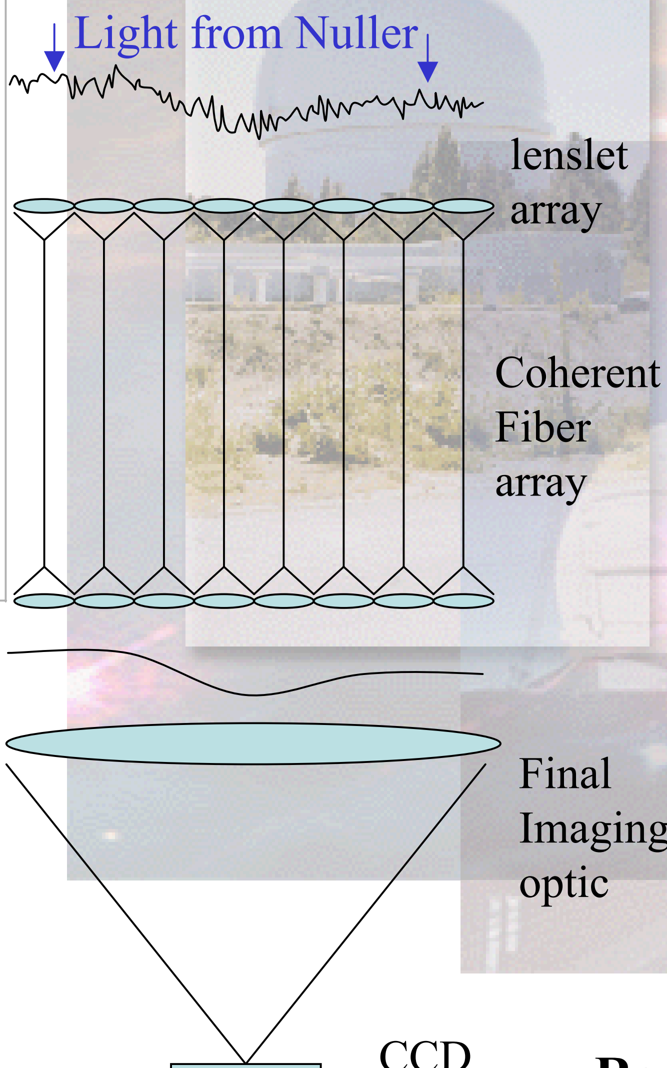

In a visible TPF based on a nulling interferometer

For Earth Detection:
Fiber array has ~ 1000 fibers

Final image plane has a field of view ~1000 airy spots (~30x30)

Average null of 1e-7 means that 1e-7 light spread over 1000 airy spots, or 1e-10 scattered light per airy spot.

Nulling requirement (Vis TPF/Earth) is
1e-7 for Q=1, planet flux = scattered light flux
3e-7 for Q=0.3

Requirement for Jupiter Imager ~10~100x easier

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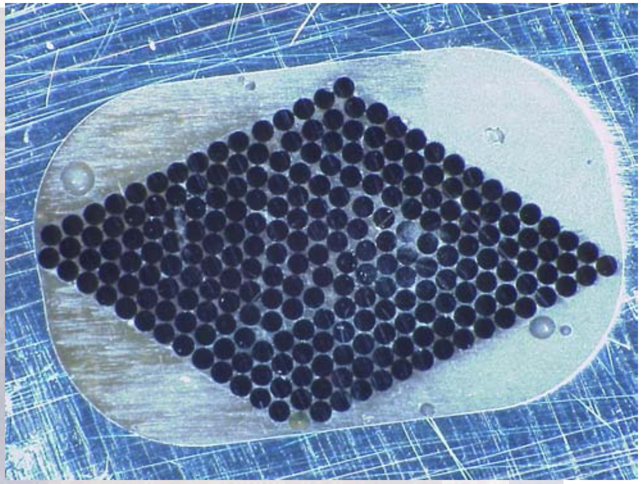
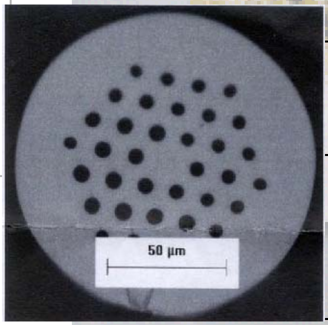
Single Mode Fiber Array Design and Characterization

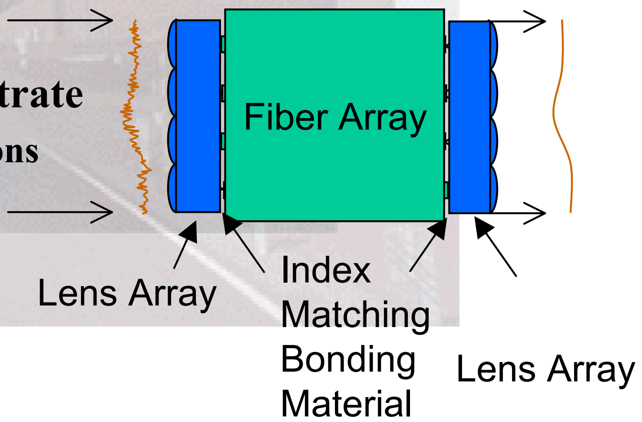
- Commercial (preliminary) fiber array results
  - Irregular gaps between fibers
    - Machine tolerance on metal housing issue
  - Useful for development of:
    - lens array to fiber alignment
    - array characterization procedures



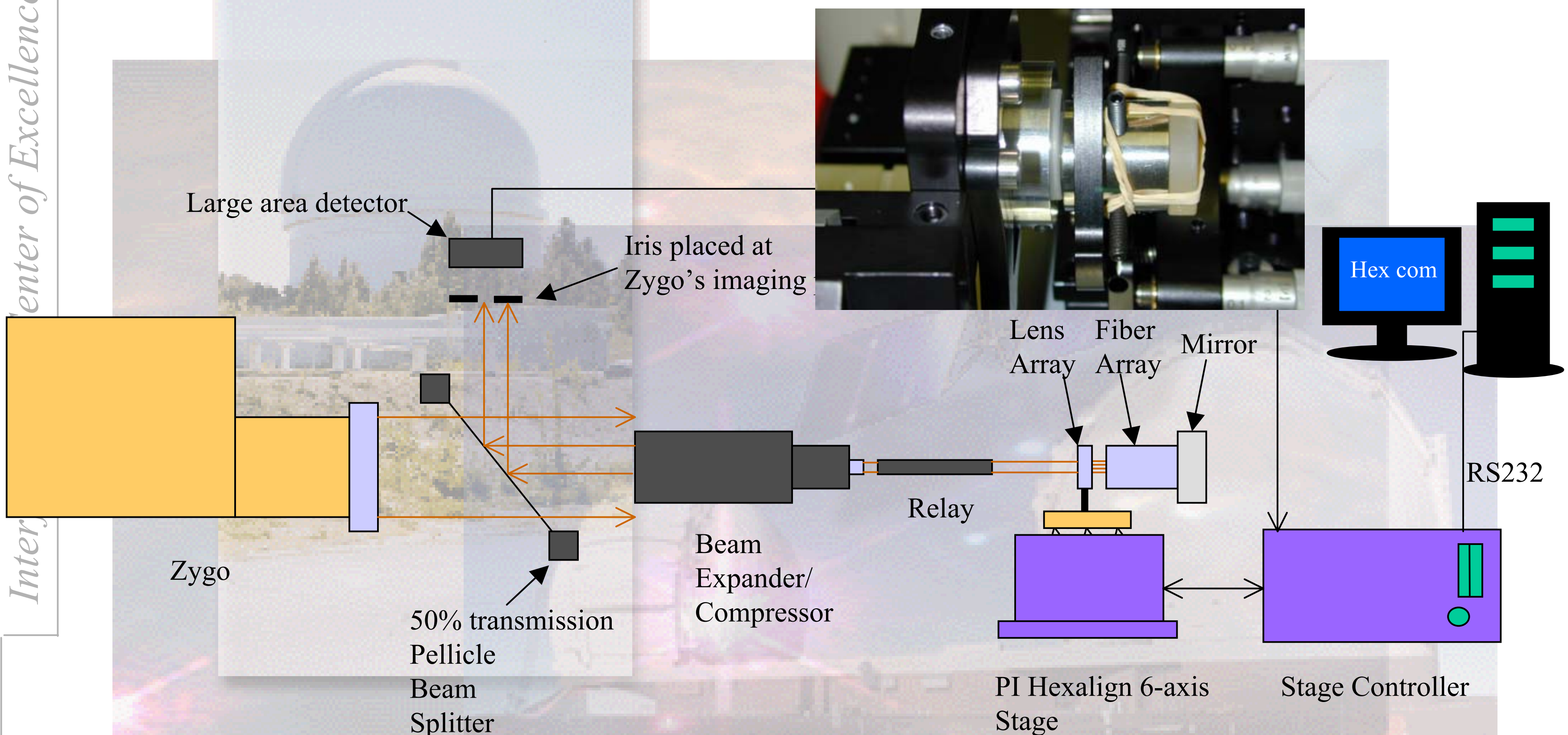
- Next Generation Array Design
  - Use large mode field diameter Photonic Crystal Fiber (PCF) to relax alignment error requirement
  - Use V-groove type fiber array construction for flexible fiber and lenslet spacing or custom self assembly fixture
  - Custom lens array with focal plane at substrate
    - Precision mapping of lenslet to fiber positions



- Assemble Using index matching bonding material to relax fiber array polishing requirement



Automated setup for simultaneous interferometery and alignment of lens array to fiber array

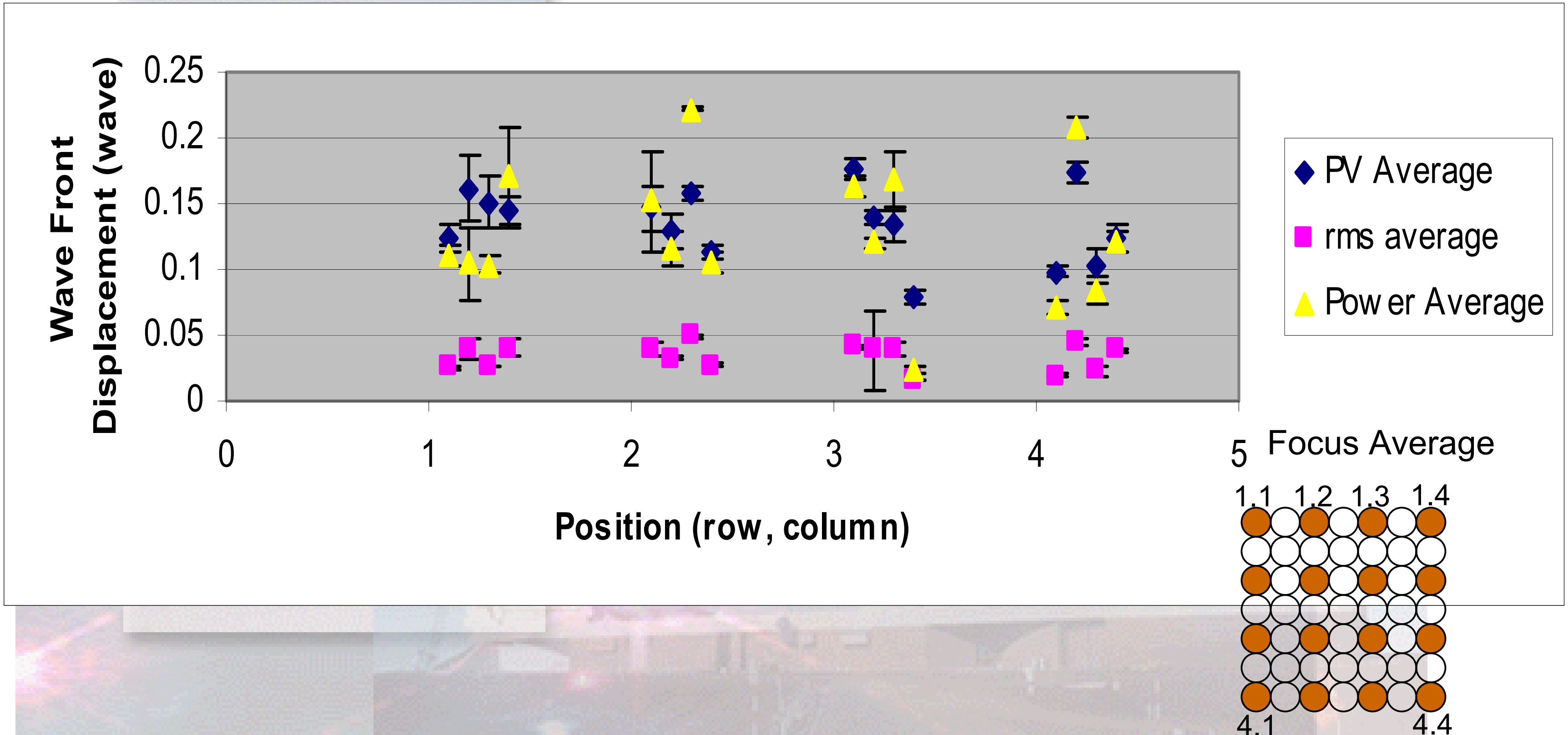


-Zygo aligns all surfaces to be parallel and aligns fiber array on focal plane

-Detector and 6-axis stage controller aligns lateral positions of lens lenslets to fibers

Zygo measurement for 16 lenses in a 7 x 7 area

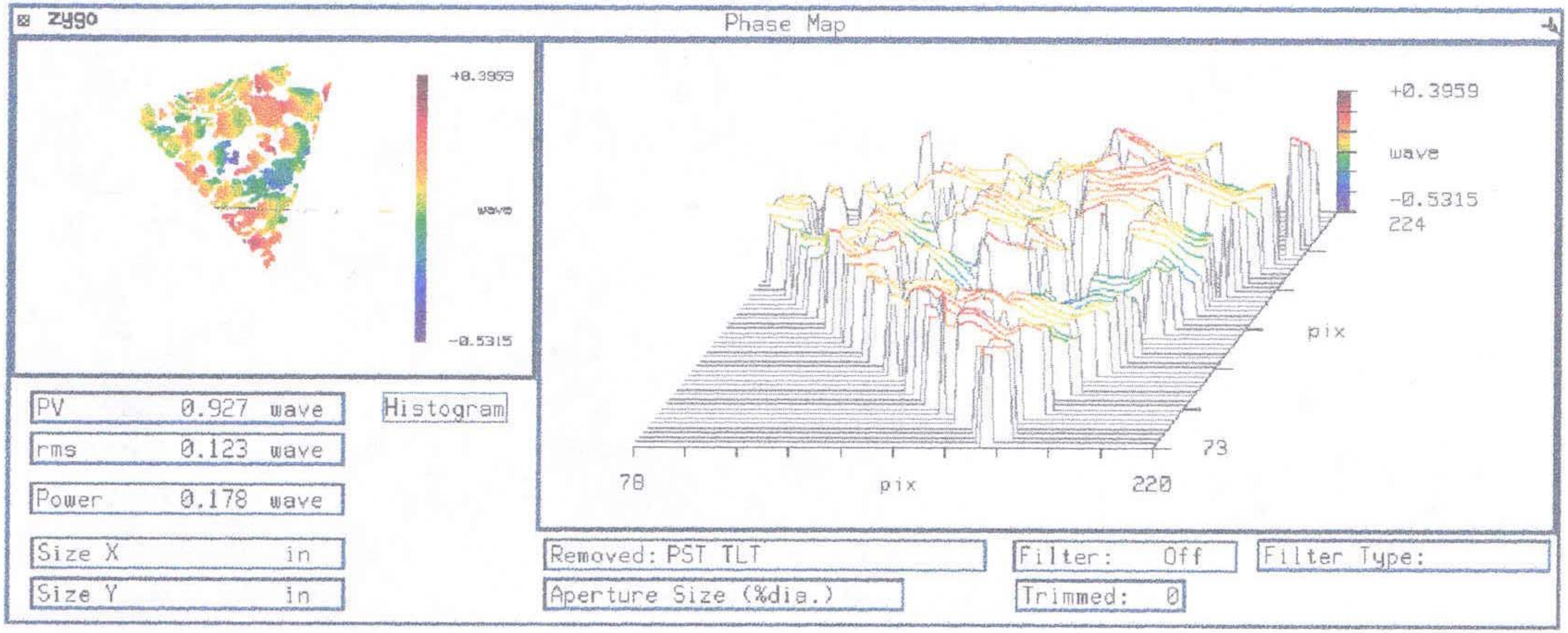
(i.e., every other lens was measured in this area)

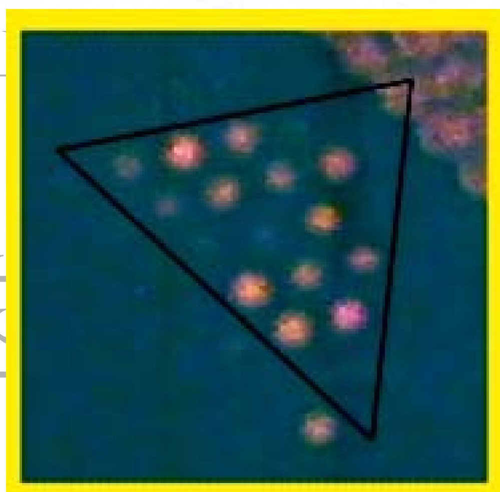


- Each data point was the average of 5 measurements.

-The error bar is given by the standard deviation of the 5 measurements

Fiber array phase measurements





- λ/8 rms wavefront error over
- ~16 contiguous subapertures
  - Coupled image from (approximate) area of phase measurement

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Summary

- **Visible Nulling Interferometer Summary**
  - **Achieved sustained null of $7x10^{-6}$, and transient null of $6x10^{-7}$**
    - **with a 1000 fiber bundle, implies scattered light in Visible TPF would be $7x10^{-9}$ and $6x10^{-10}$ per Airy spot, respectively.**
  - **Closed-loop metrology systems under integration**

- **<u>Only a factor of 2~6 away from what is needed in a visible TPF with a 4m primary, to detect Earths around solar like stars at 10pc.</u>**

- **Single Mode Fiber Array Summary**
  - **Lenslet array center-to-center spacing measured to ±1.33μm**
    - **Repeatability is ± 0.22 μm**
  - **In process to build 20 SMF array with PCF's**
    - **5x decrease in position tolerance on lenslet array and alignment**