The Visible Nulling Coronagraph--Progress Towards Mission and Technology Development

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Abstract: This paper describes a space mission for visible direct detection and spectroscopy of Earth like extrasolar planets using a nulling coronagraph instrument behind a moderately sized (~4m) telescope in space. In our design, a 4 beam nulling interferometer is synthesized from the telescope pupil, producing a deep null proportional to θ^4 which is then filtered by a coherent array of single mode fibers to suppress the residual scattered light. With diffraction limited telescope optics and similar quality components in the optical train ($\lambda/20$), suppression of the starlight to 10^{-10} is achievable. We describe key features of the basic analysis, show how this effects a space mission design, present latest results of laboratory measurements demonstrating achievable null depth and component development, and discuss future key technical milestones.

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Large Apertures are NOT Needed in Principle to Detect and Characterize Extra-solar Planets

- **A modest sized aperture telescope can theoretically resolve an extra-solar planet**
  - **Jupiters at 10 pc $D > 0.3$m (λ=0.75mm)**
  - **Earths at 10 pc $D > 1.5$ m**
- **The HST (at 2.4m diameter) is capable of imaging m_v=30 stars**
- **The major issue is overcoming the contrast between star and planet (10^{-9}-10^{-10})**
  - (10^{-9} for exo-Jupiters)

Why Another Coronagraph Concept?

- Nulling interferometer/coronagraph belongs in a class of small inner working distance devices
- Use 4~5m telescopes instead of 8~10 m telescopes for the TPF mission.
  - If a **4m telescope is $X** dollars (X large), and if the cost of a telescope goes as **$D^{2.5}$** the cost of a 8-10m telescope is very (very) large.
- **Orders of magnitude** easier to control scattered light, at the required constrast of 10^{-10} per airy spot
  - Amplitude
  - Phase
  - Spectral width
  - Polarization

Planet Detection with a Nulling Interferometer

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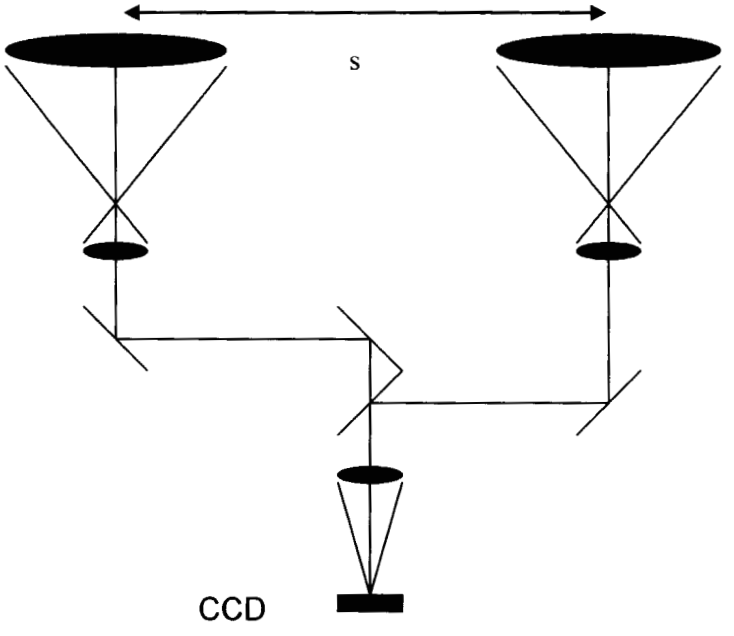

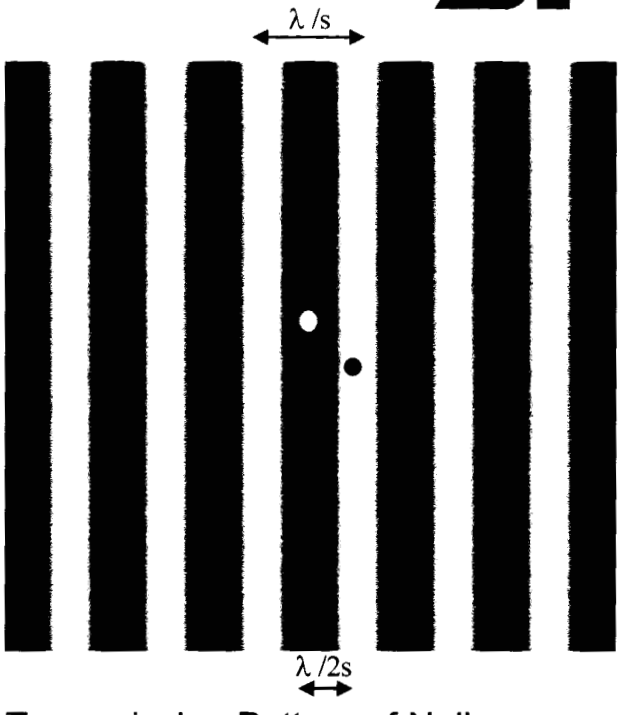

Transmission Pattern of Nuller
On the sky. (Star is at the center)

- When the light from two pupils are combined, the output can be imaged.
- The image is an Airy function with diameter 2.44λ/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 or more telescopes**

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2-arm vs. 4-arm Nulling Interferometers

2 arm:

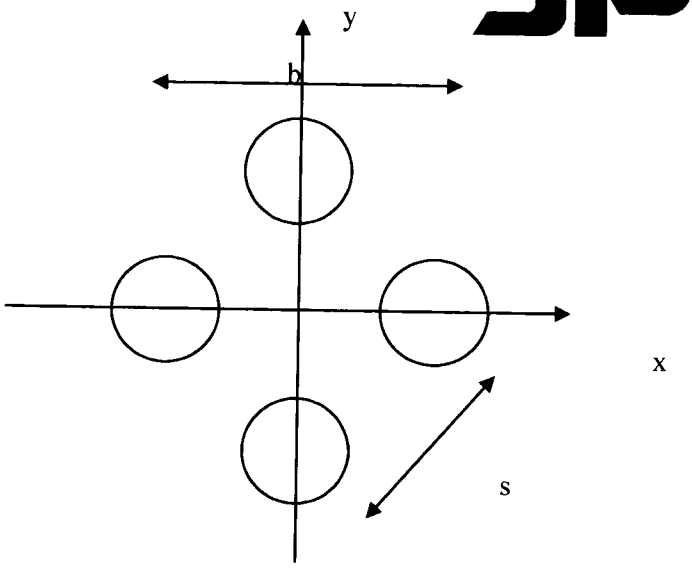
$$I = \left| A_0 e^{i\phi_x} - A_0 e^{-i\phi_x} \right|^2$$

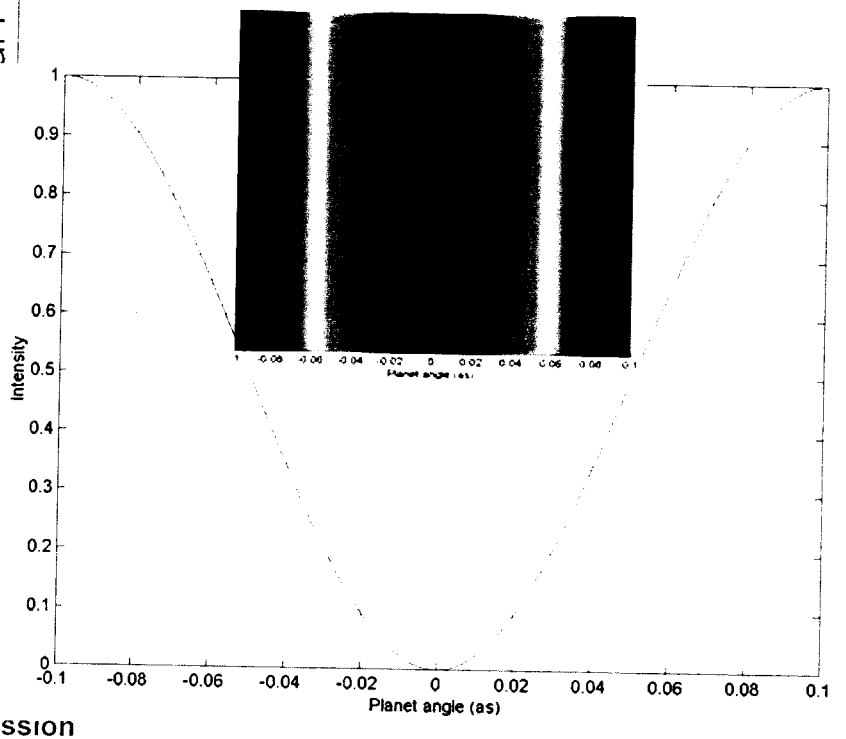
$$\approx I_0 \left(ks \cos \phi \right)^2 \theta^2$$

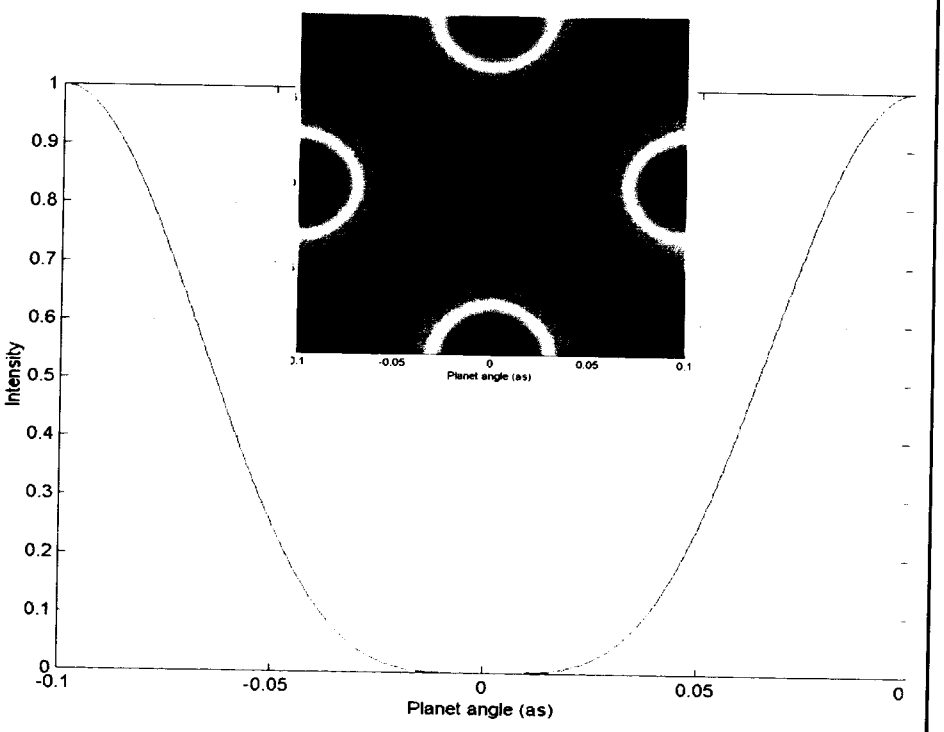
4 arm:

$$I = \left| A_0 e^{i\phi_x} - A_0 e^{-i\phi_x} + A_0 e^{i\phi_y} - A_0 e^{-i\phi_y} \right|^2$$

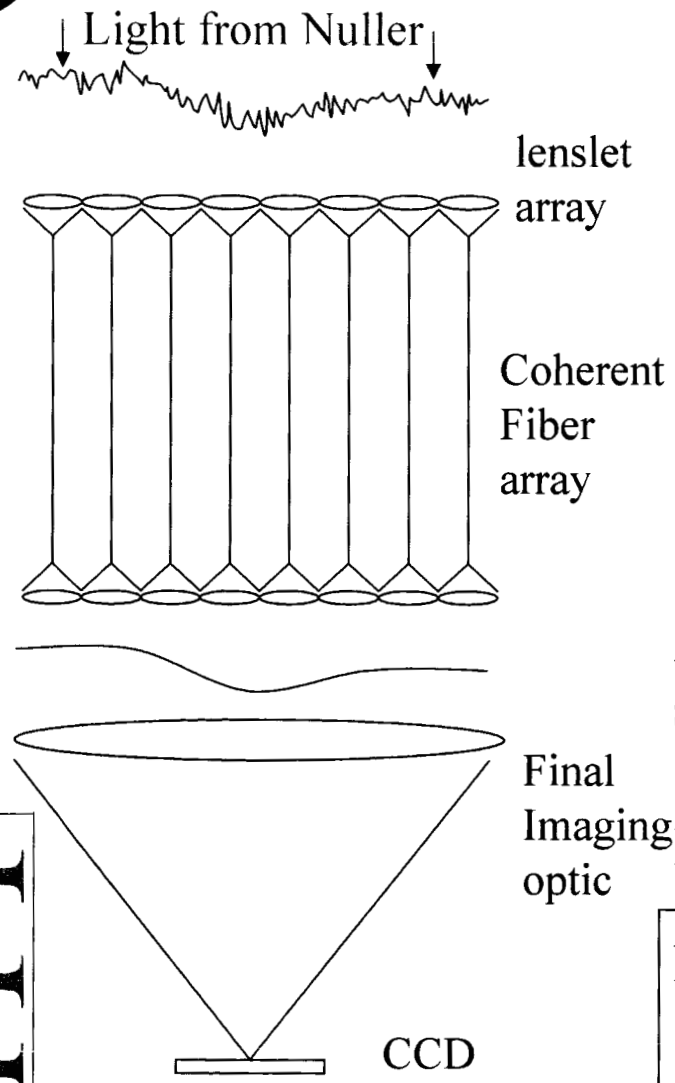
$$\approx I_0 \left(\frac{kb}{2} \right)^4 \cos^2(2\phi) \theta^4$$







Coherent Fiber Array Nulling Requirements



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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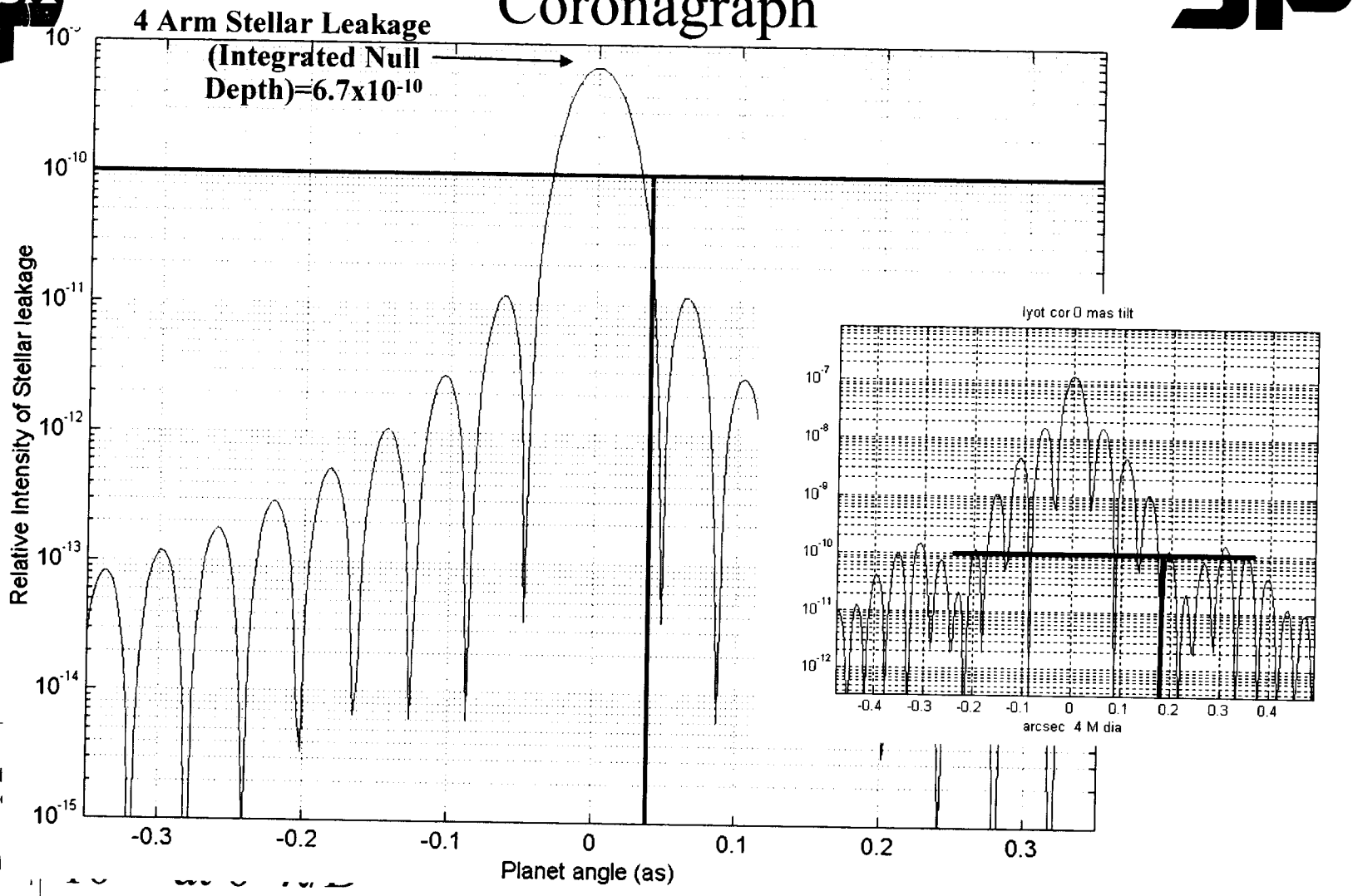
Ideal performance of Visible Nulling Coronagraph



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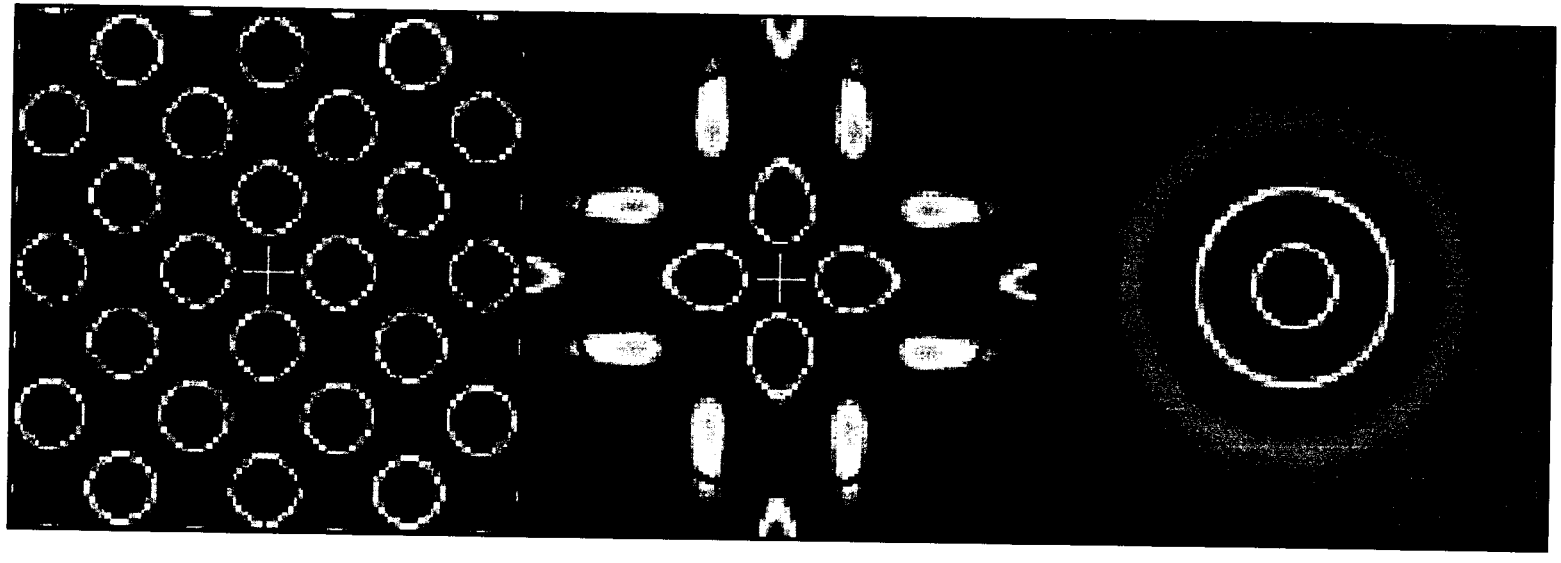
Simulated Nulling Coronagraphic Imaging



Monochromatic Null | Polychromatic Null | Rotated Null

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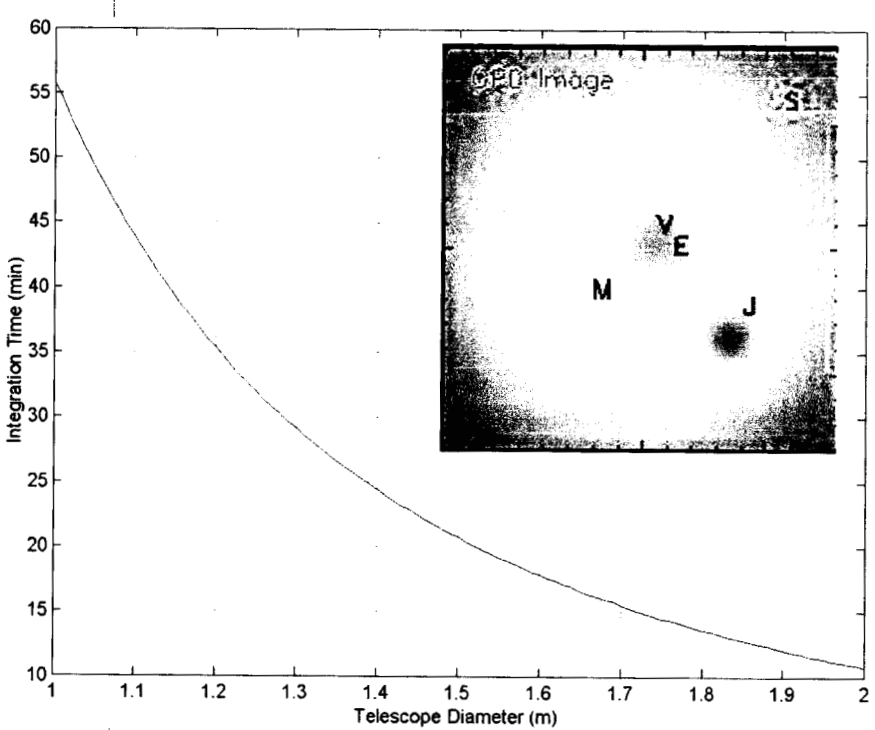
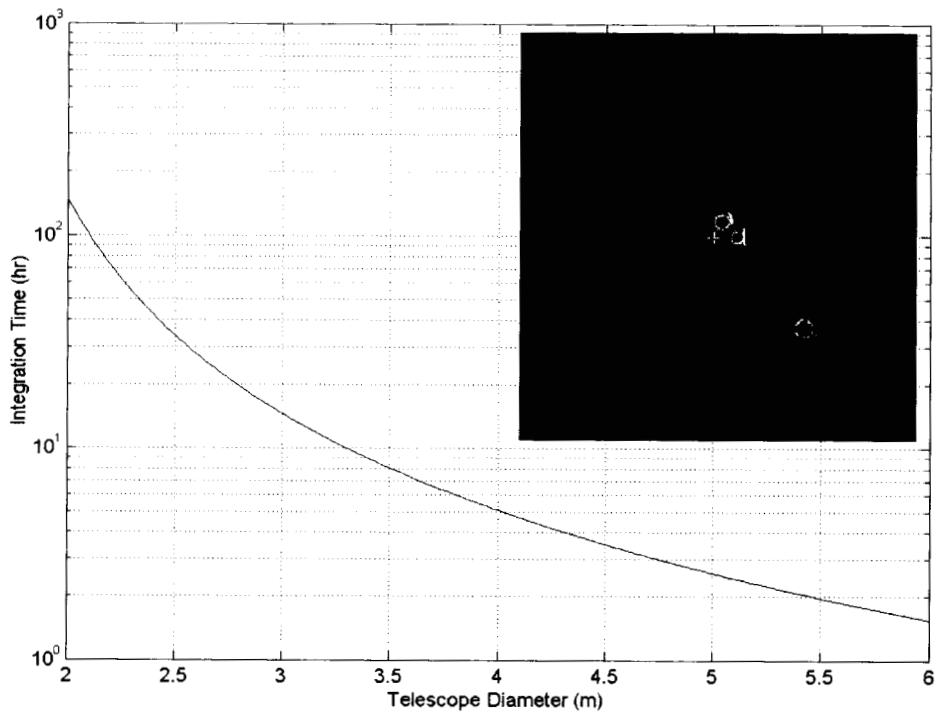
Imaging Simulations (Velusamy) & Integration Time for SNR=5

Simulated image of our solar system at 10pc



1.5m telescope



4.0m telescope

- Nulling Coronagraph does not rely on paradigm that large apertures are required for TPF science

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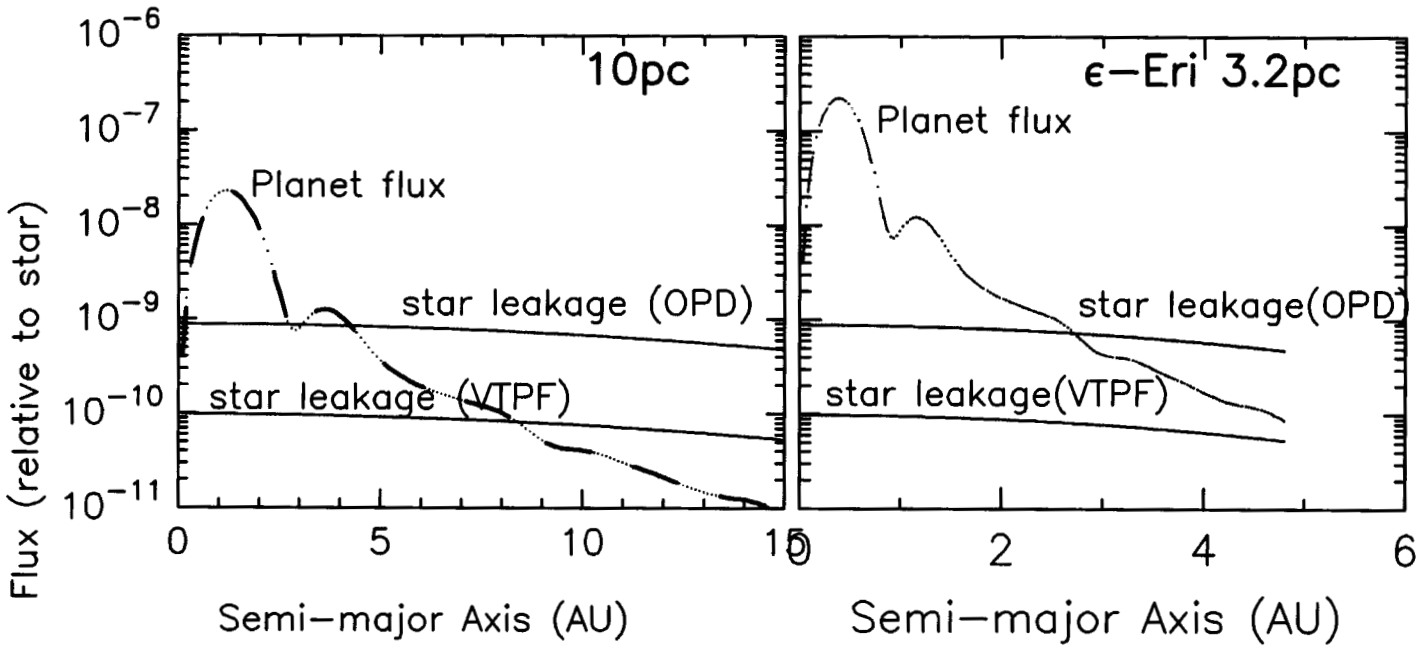
Imaging Capability



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.

Functional Overview of Nulling Coronagraph

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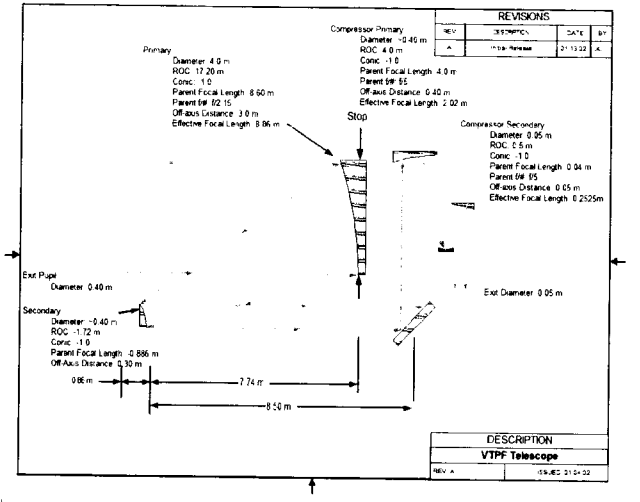
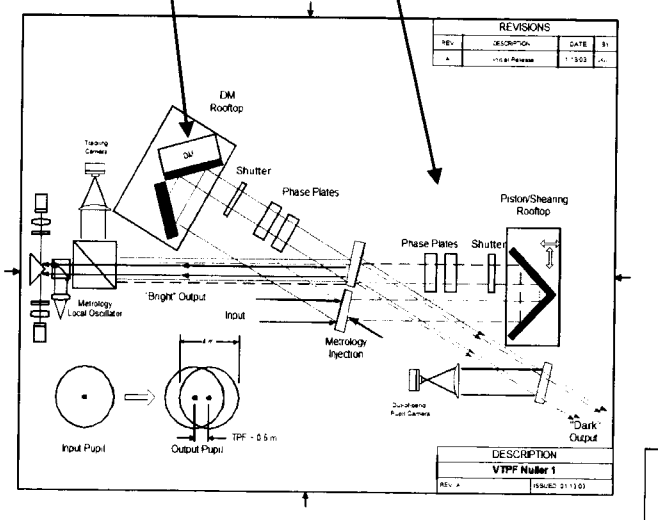


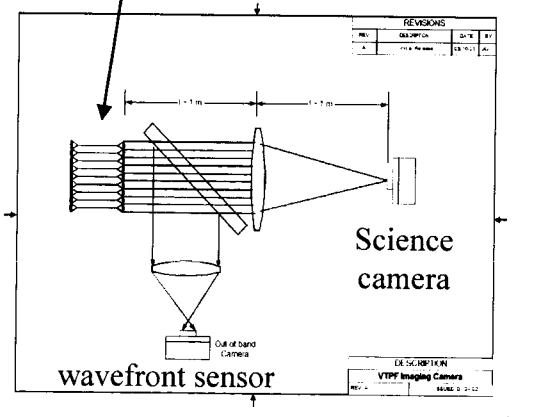
Beam Compressor

Nulling Interferometer subsystem

DM



Coherent Fiber Bundle



Primary reimaged to DM's which are in turn reimaged to the input lenslet array. The output lenslet array is reimaged to the wavefront sensor CCD. (reimaging to eliminate xtalk between channels)

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Boston University MEMS Deformable Mirror Prototype

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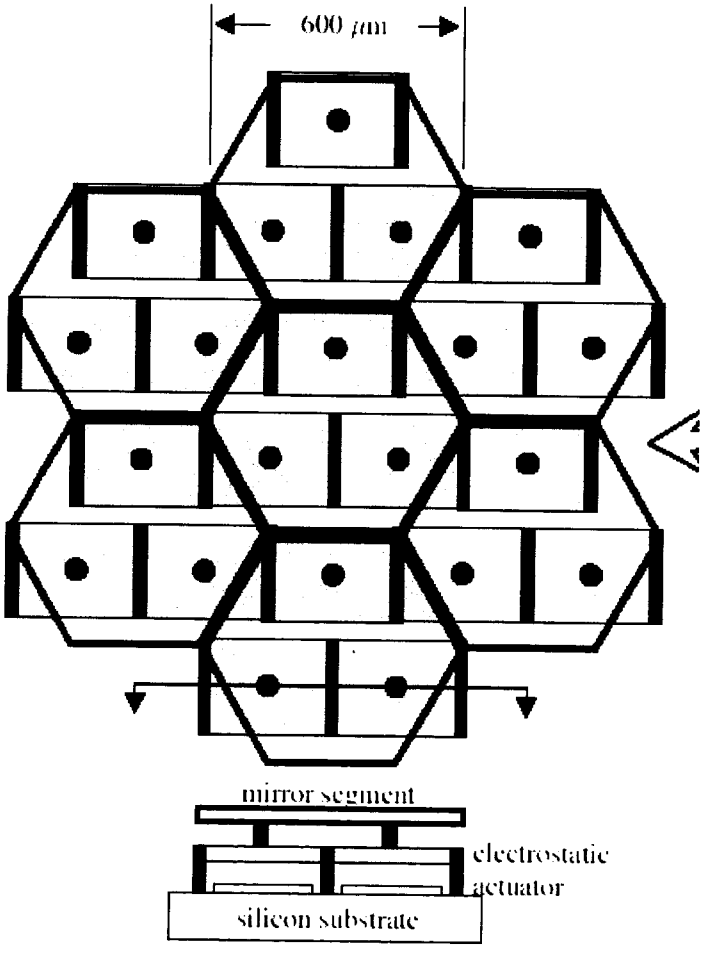
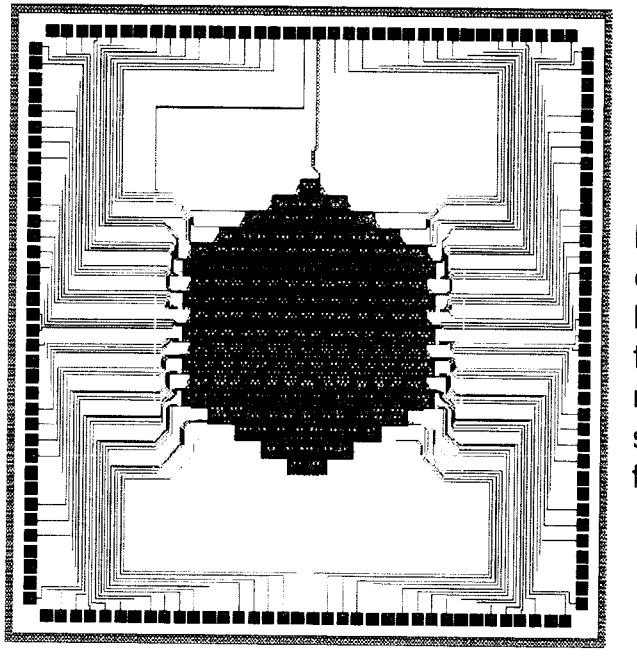
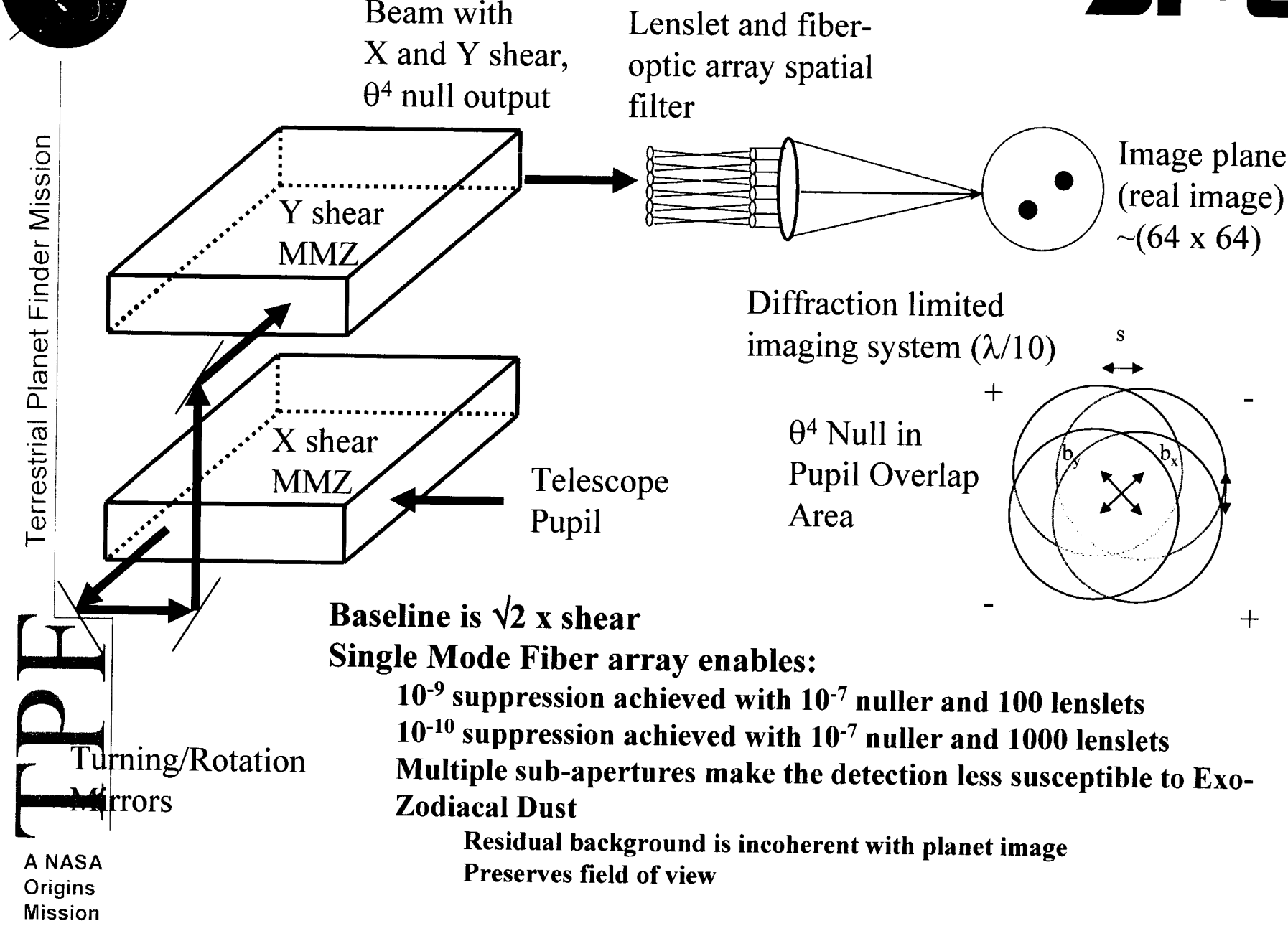


61 Pixel TPF Array



Mask designs complete: Mirror in fabrication now at MEMS silicon foundry

Visible Nulling System Concept



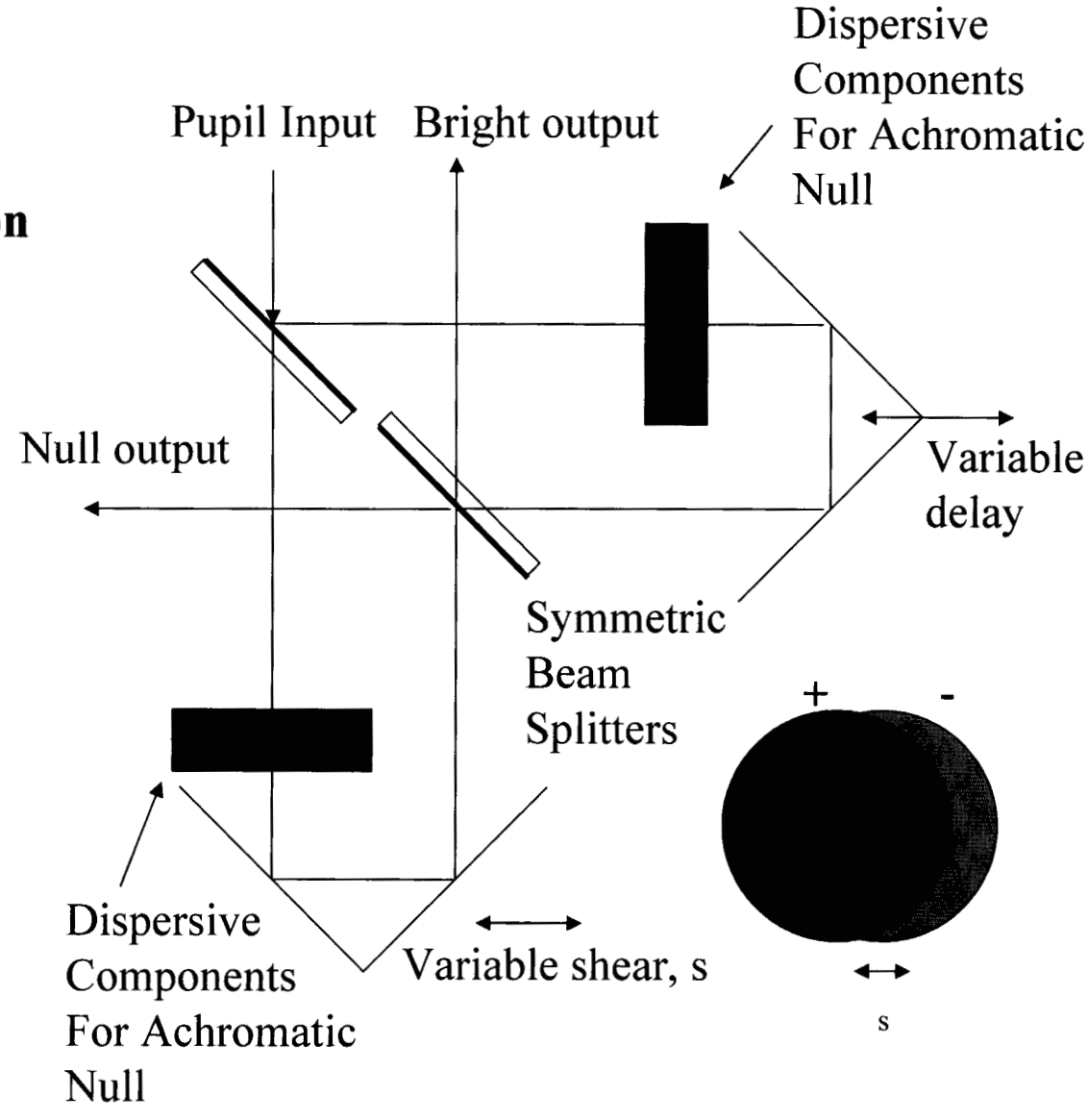
Baseline is $\sqrt{2}$ x shear

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 (Shao & Serabyn)

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



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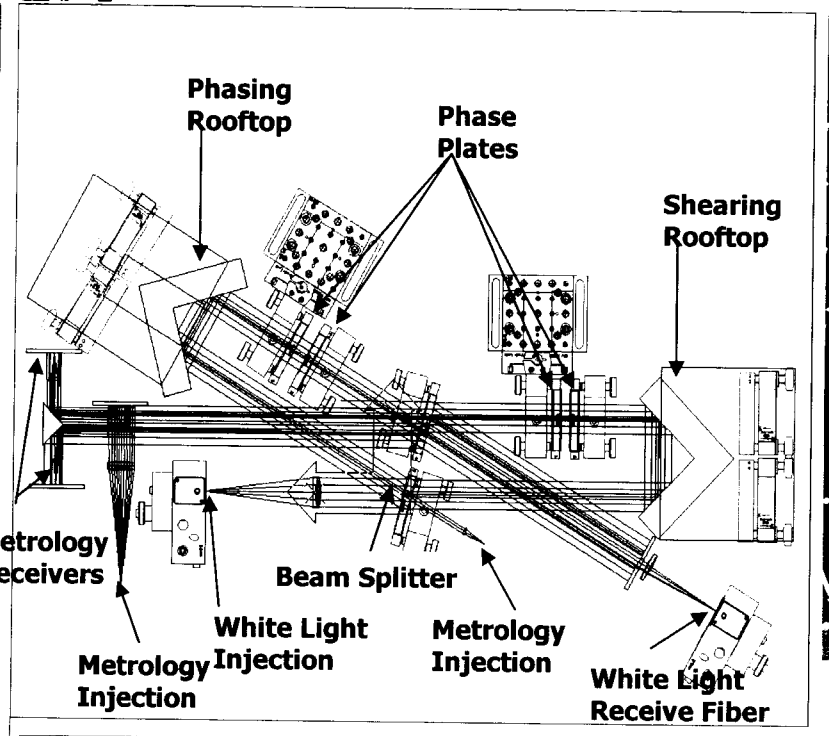
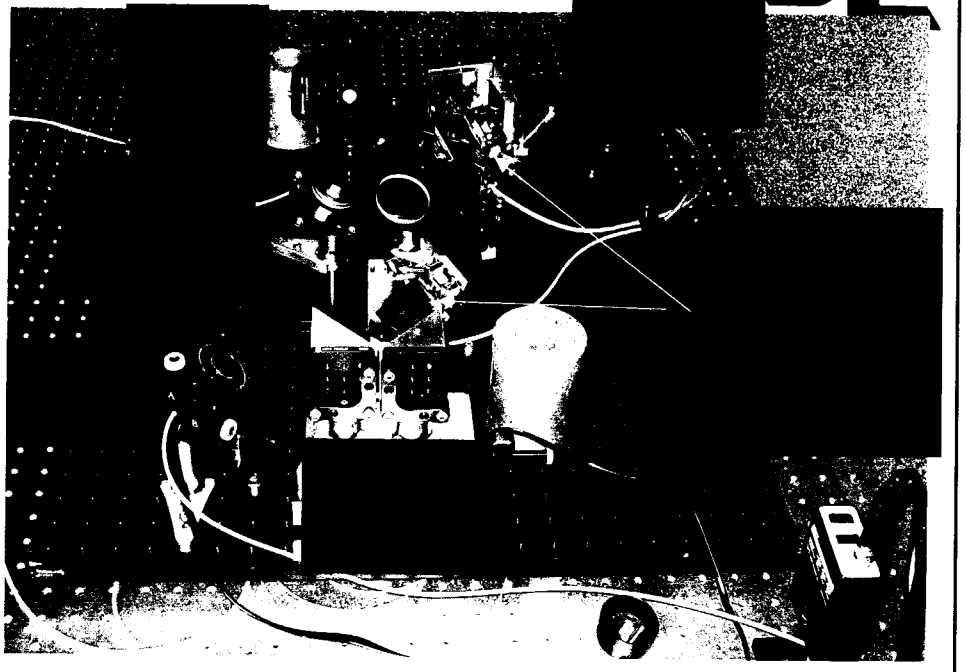
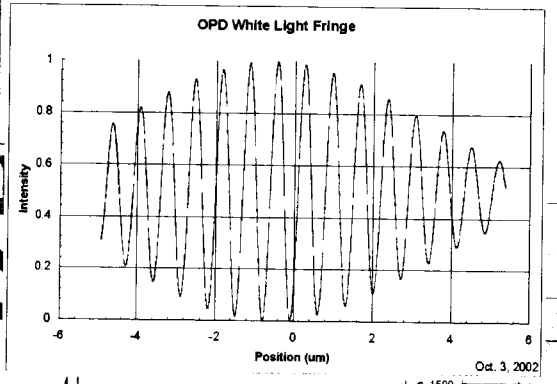
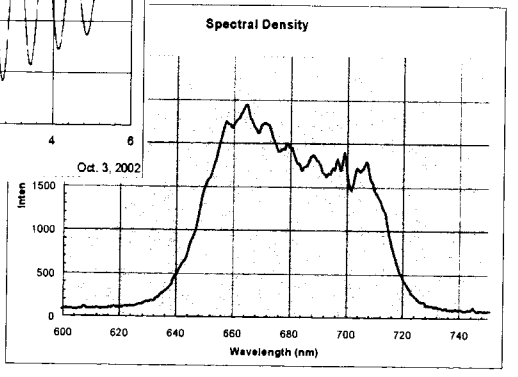
Proof of Concept Nulling Interferometer









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

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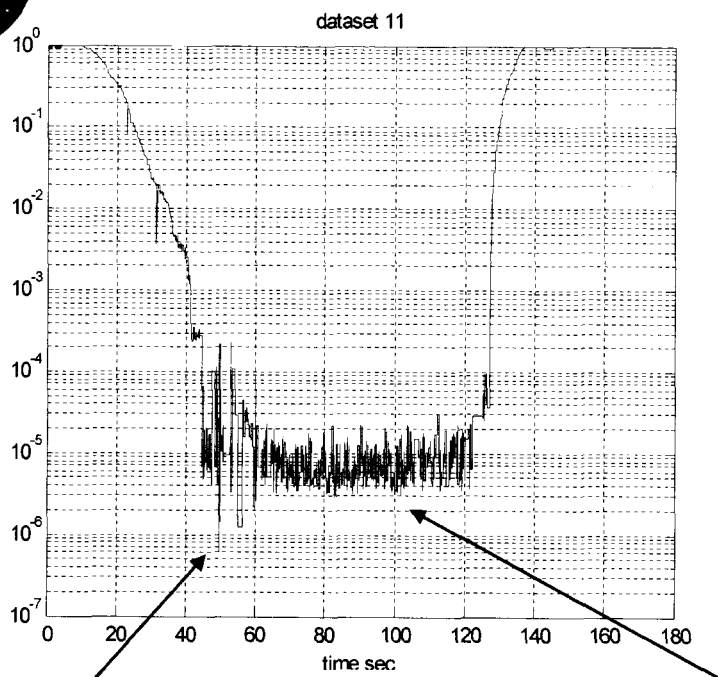
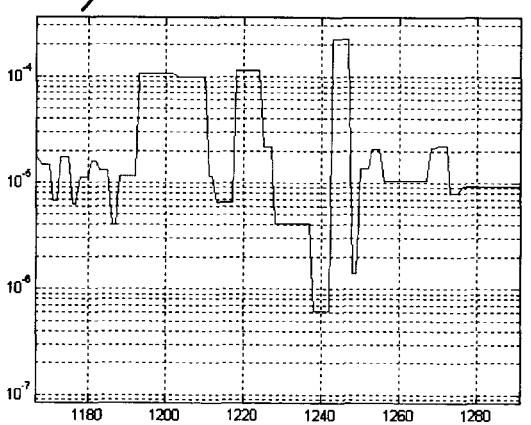
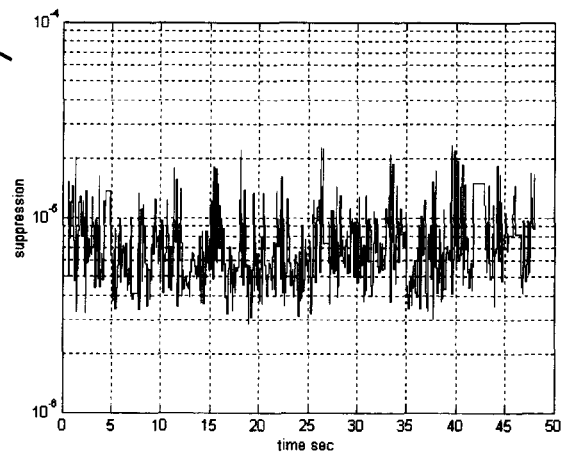
Deep Nulls from Monochromatic Light



- 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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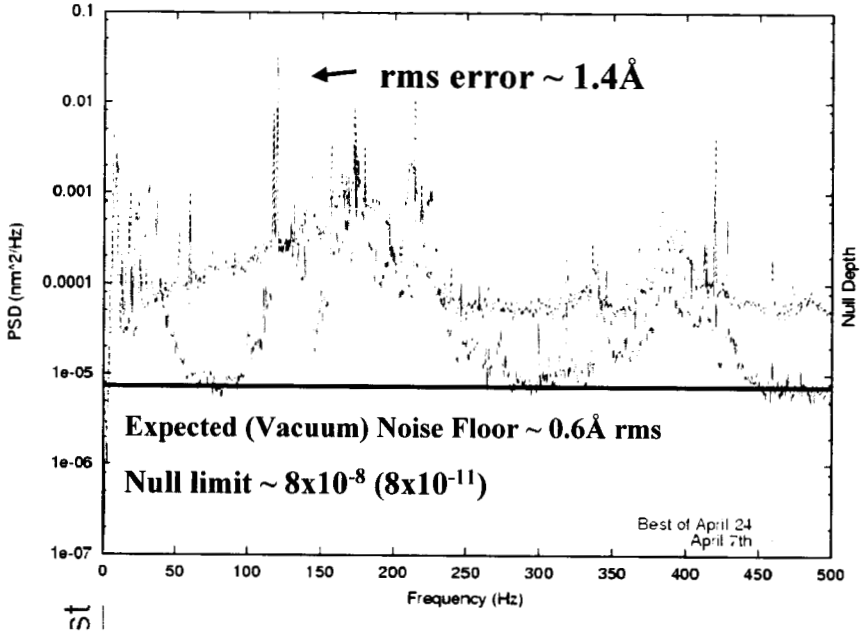
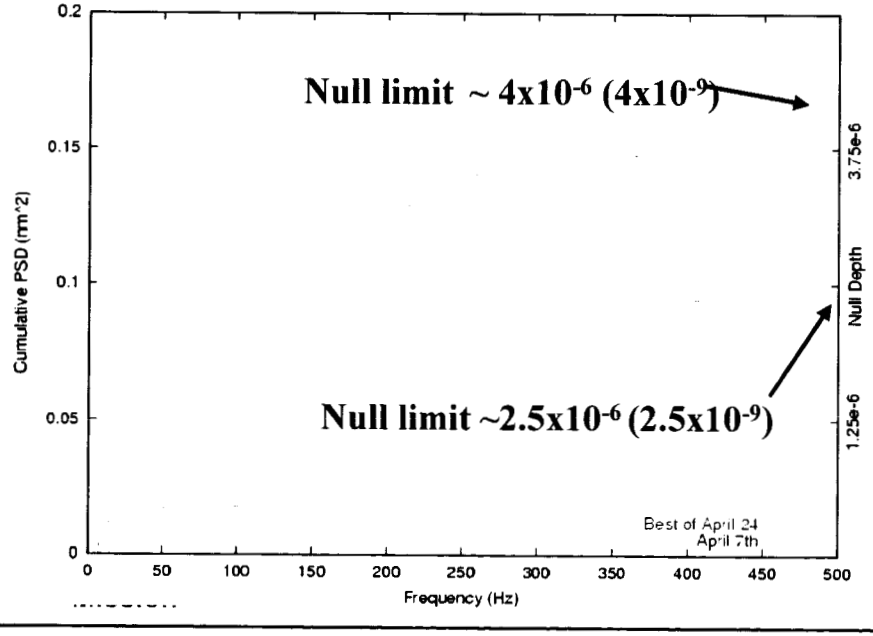
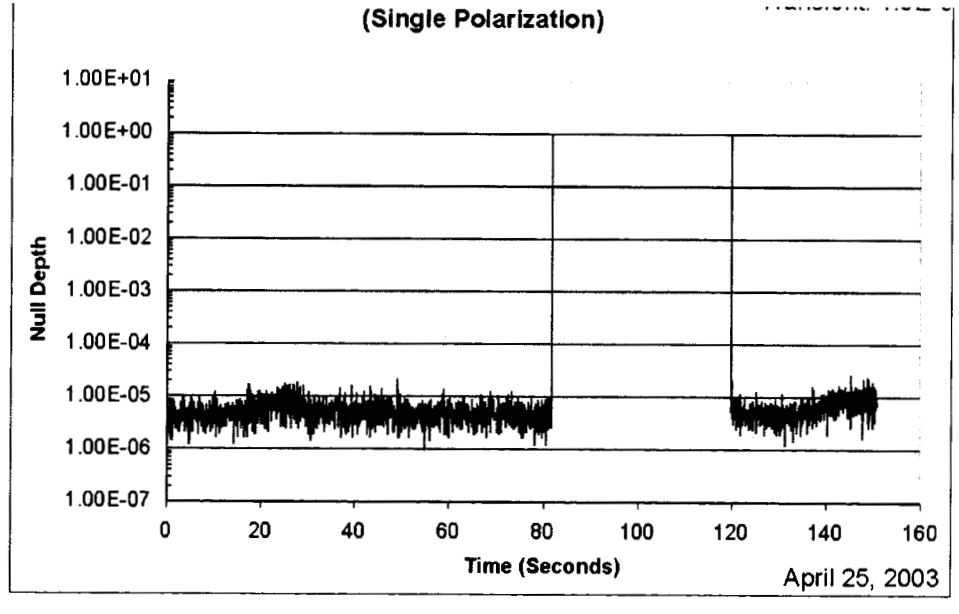
Deep Null Controlled by Laser Metrology



$$null\ depth \approx \frac{\sigma_\phi^2}{4} \qquad \lambda = 635\text{nm}$$

- **Average null = 5.2×10^{-6} (5.2×10^{-9})**
  - **50x from TPF goal**
  - **See SPIE 5170-21, Wallace et. al**





Recent White Light Null Results

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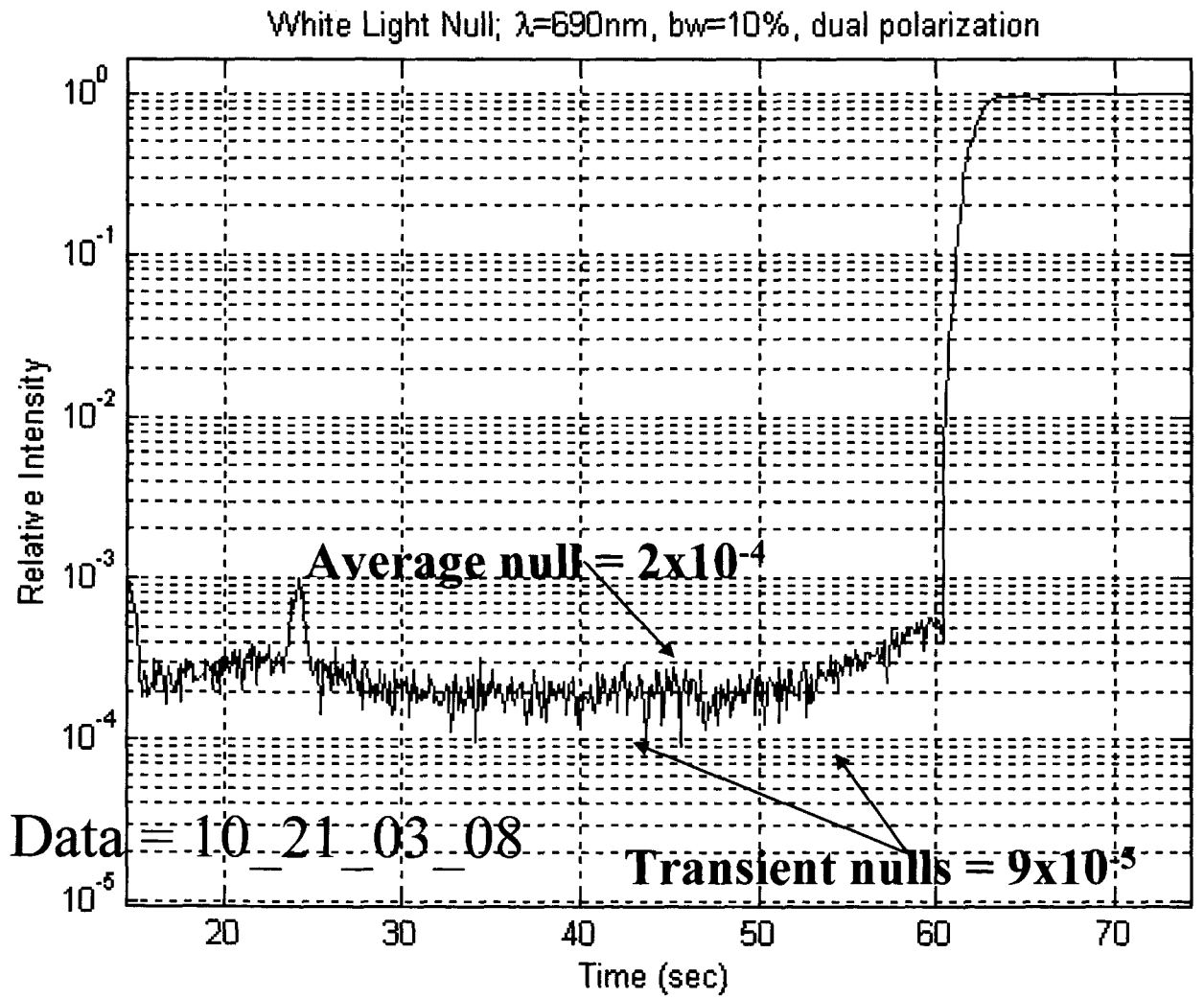

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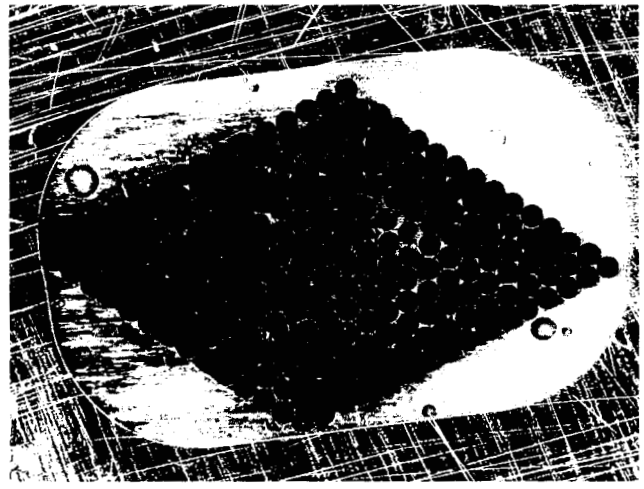
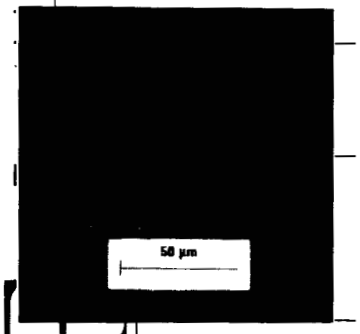
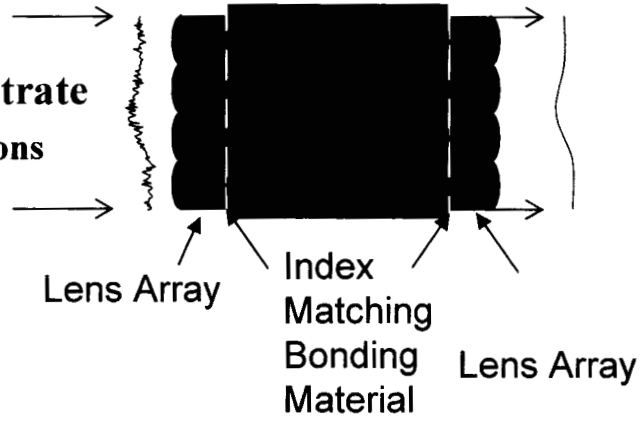
Single Mode Fiber Array Design and Characterization

- 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

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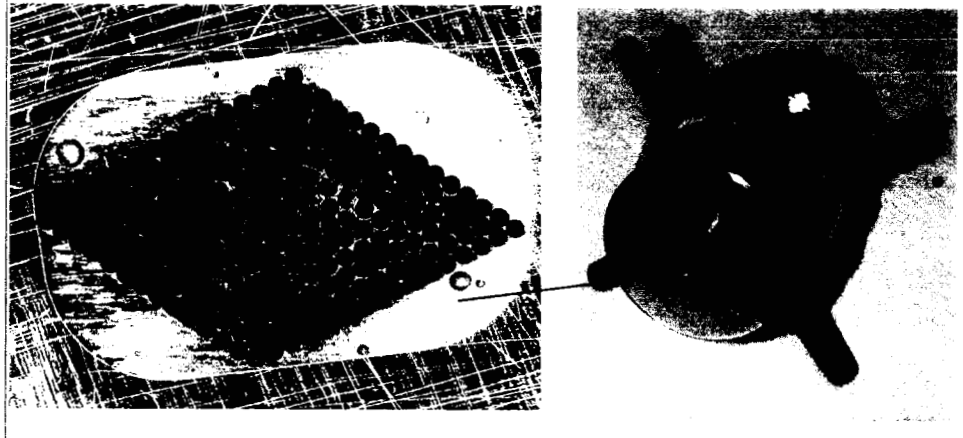
1st Generation fiber and lens array

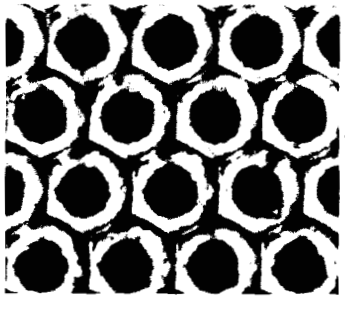
Vendors: Fiberoptic System: $3,000, AOA $1000 (commercial best efforts)



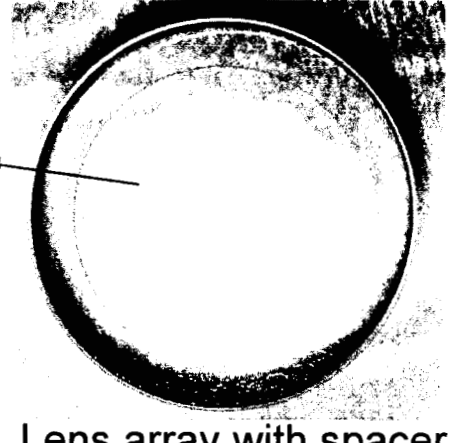
- **Array Properties**
  - **Number of fibers:** ~200
  - **Length**: 1 inch
  - **Fiber spacing**: ~126 mm
  - **Housing**: stainless steel

Commercial (preliminary) fiber array results:

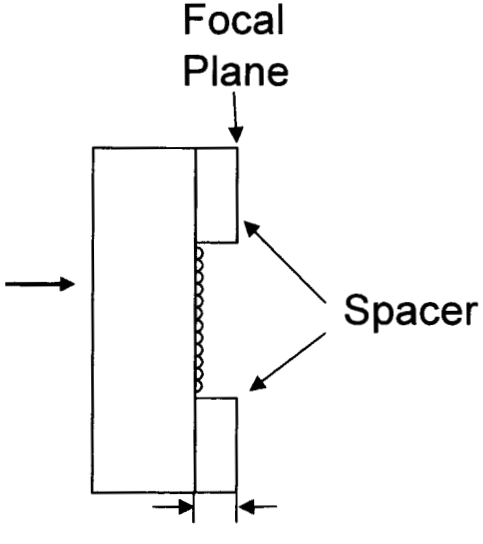
- **Irregular gaps between fibers**
  - **Machine tolerance on metal housing issue**
- **Useful for development of:**
  - **lens array to fiber alignment**
  - **array characterization procedures**



Lenslets



Lens array with spacer



Side view (not to scale)

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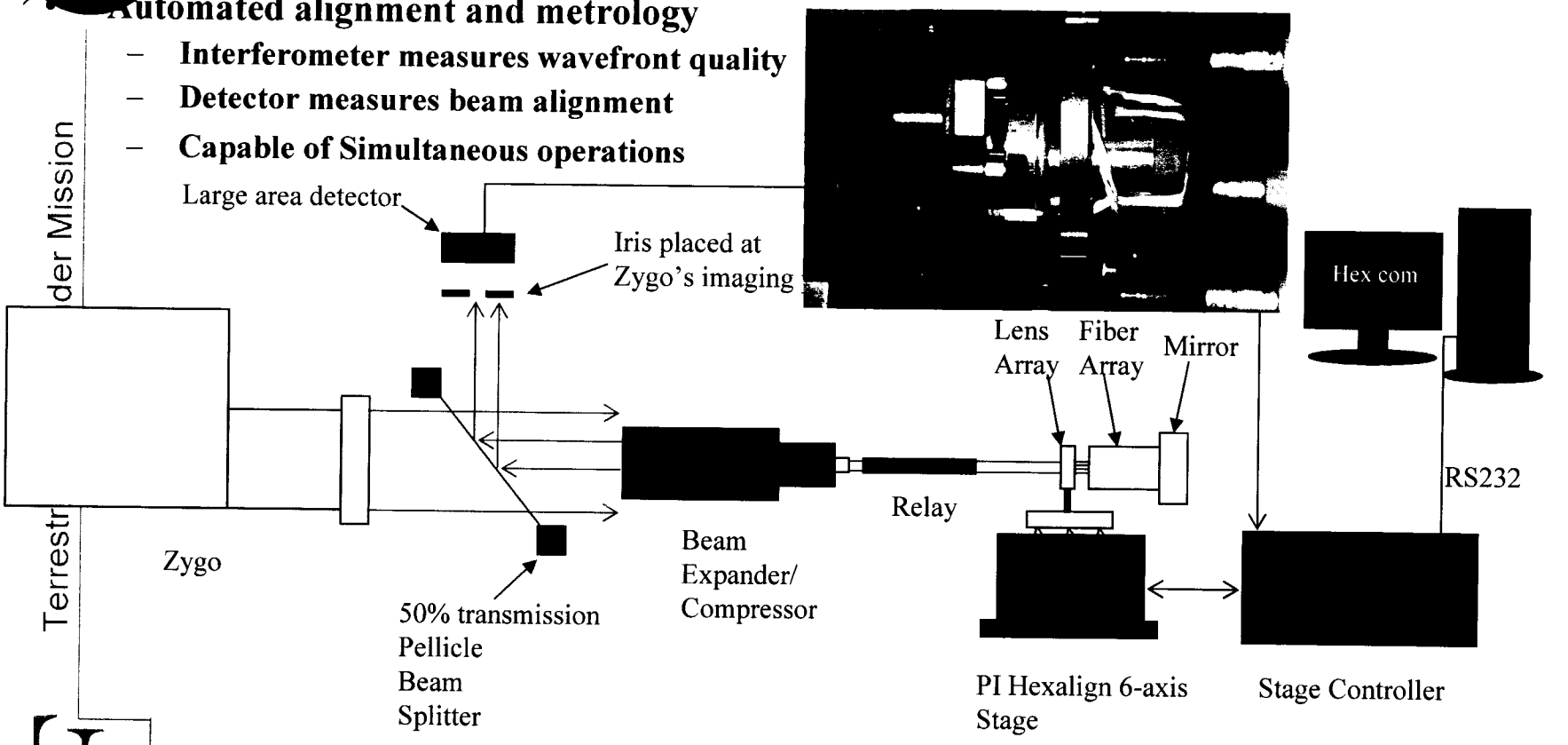
Automated setup for simultaneous interferometery and alignment of lens array to fiber array

- Automated alignment and metrology
  - Interferometer measures wavefront quality
  - Detector measures beam alignment
  - Capable of Simultaneous operations



-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

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Self Assembly of Fibers in (2nd Generation) Coherent Array (Liu)

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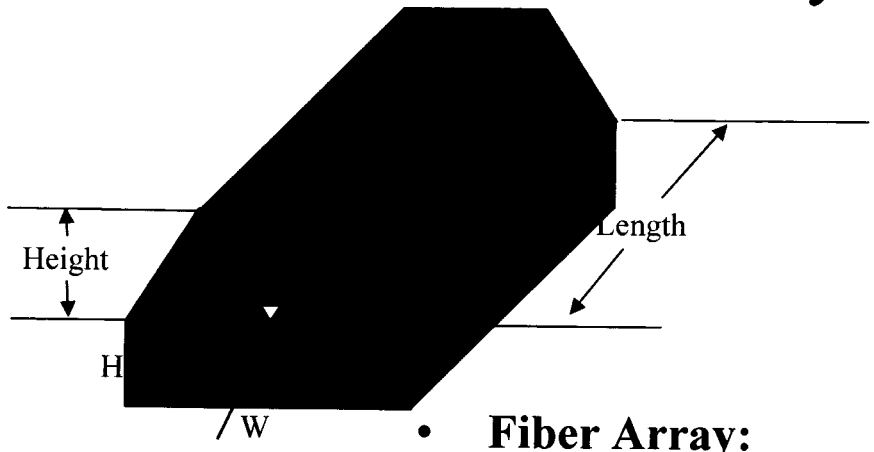
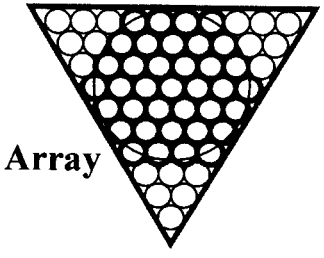
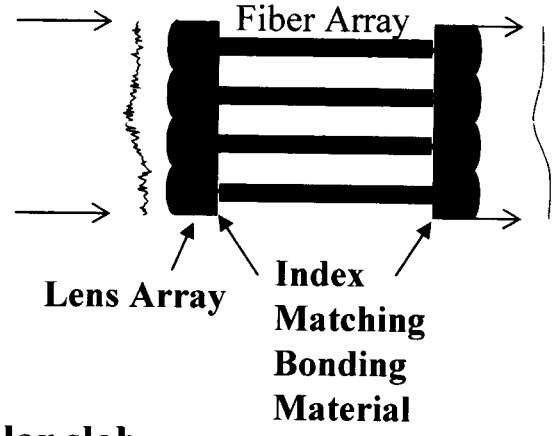


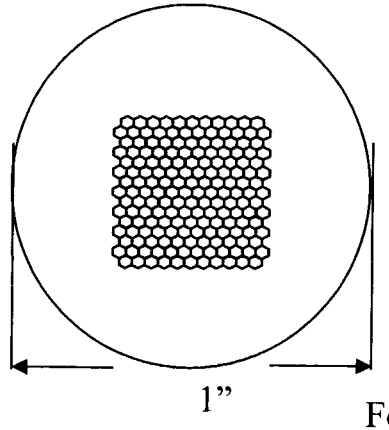


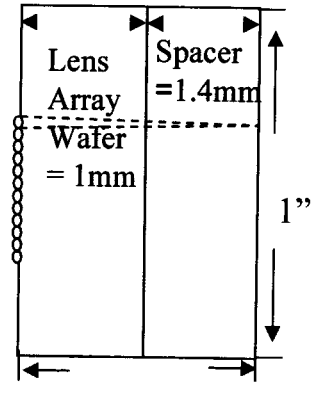
•Fiber Array Detail



- **Fiber Array:**
  - **3 Dove prisms on rectangular slab**
  - **Prism 2 corner is cut flat to accommodate Fibers**
  - **New Technology Report filed**

- **Lens Array**
  - **Monolithic Lens Array on thin substrate**
  - **Spacer bonded with thickness = focal length**
  - **Lens spacing 126.2μm**
  - **NA=0.048 @λ=0.632μm**





Focal length = 2.4 mm

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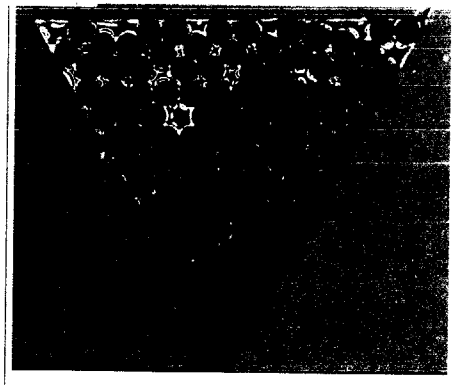
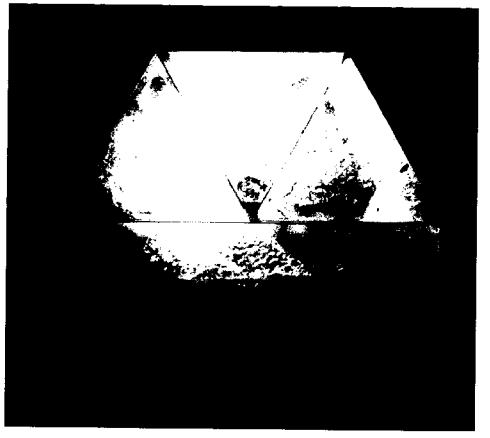
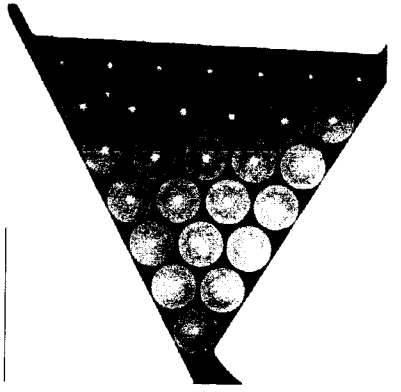
See SPIE 5170-22, Liu et. al

Single Mode Fiber Array Construction

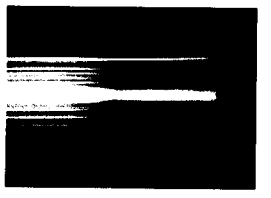


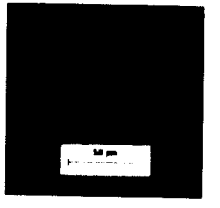


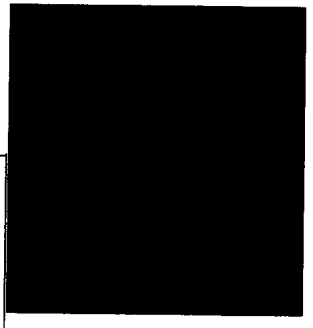


63 (Conventional) Single Mode Fibers

28 Photonic Crystal Fibers







- Far-field mode pattern from lens array coupled fibers
- λ/15rms wavefront error over all apertures

- Use large mode field diameter Photonic Crystal Fiber (PCF)
  - to relax alignment error requirement
  - Fuse ends to accommodate array polish
- Large cladding diameter, large MFD, step-index single mode fibers may be low-cost alternative to PCF solution for building large 1000 sub-aperture spatial filter

Prototype Fiber Array #2 Regularity

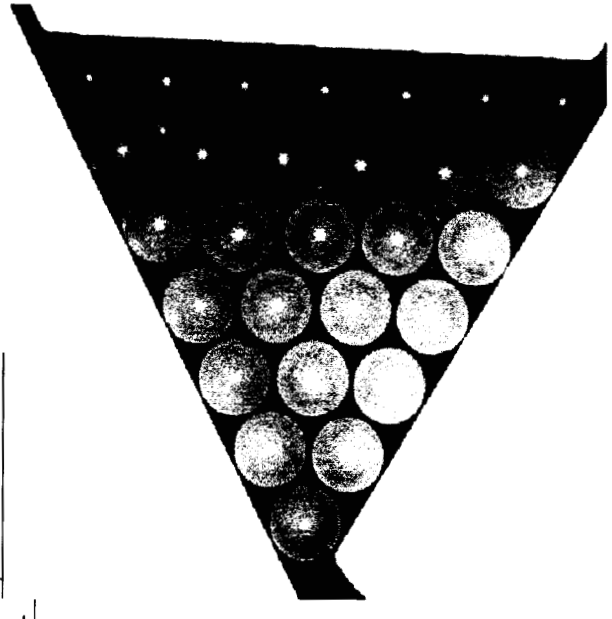
Photonic Crystal Fibers (PCF)

Terrestrial Planet Finder Mission

TPF

A NASA Origins Mission

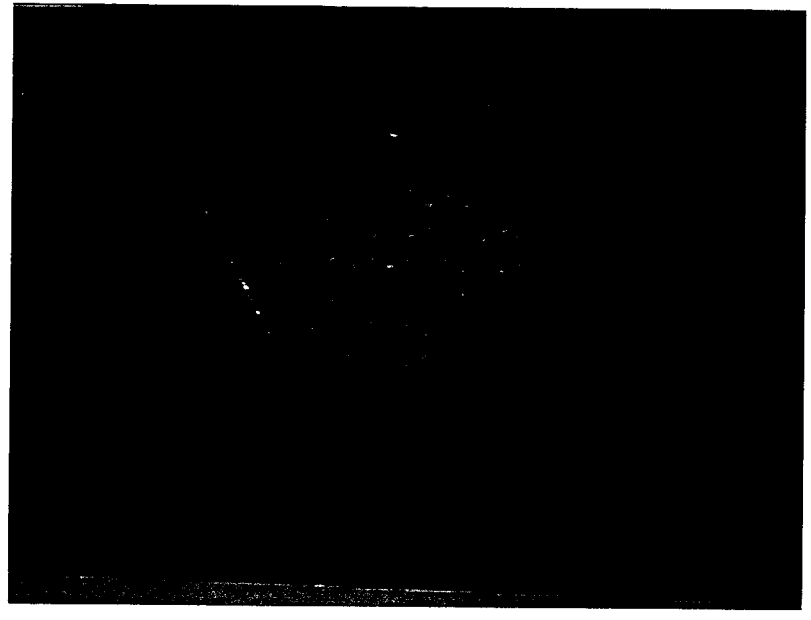
Array Image



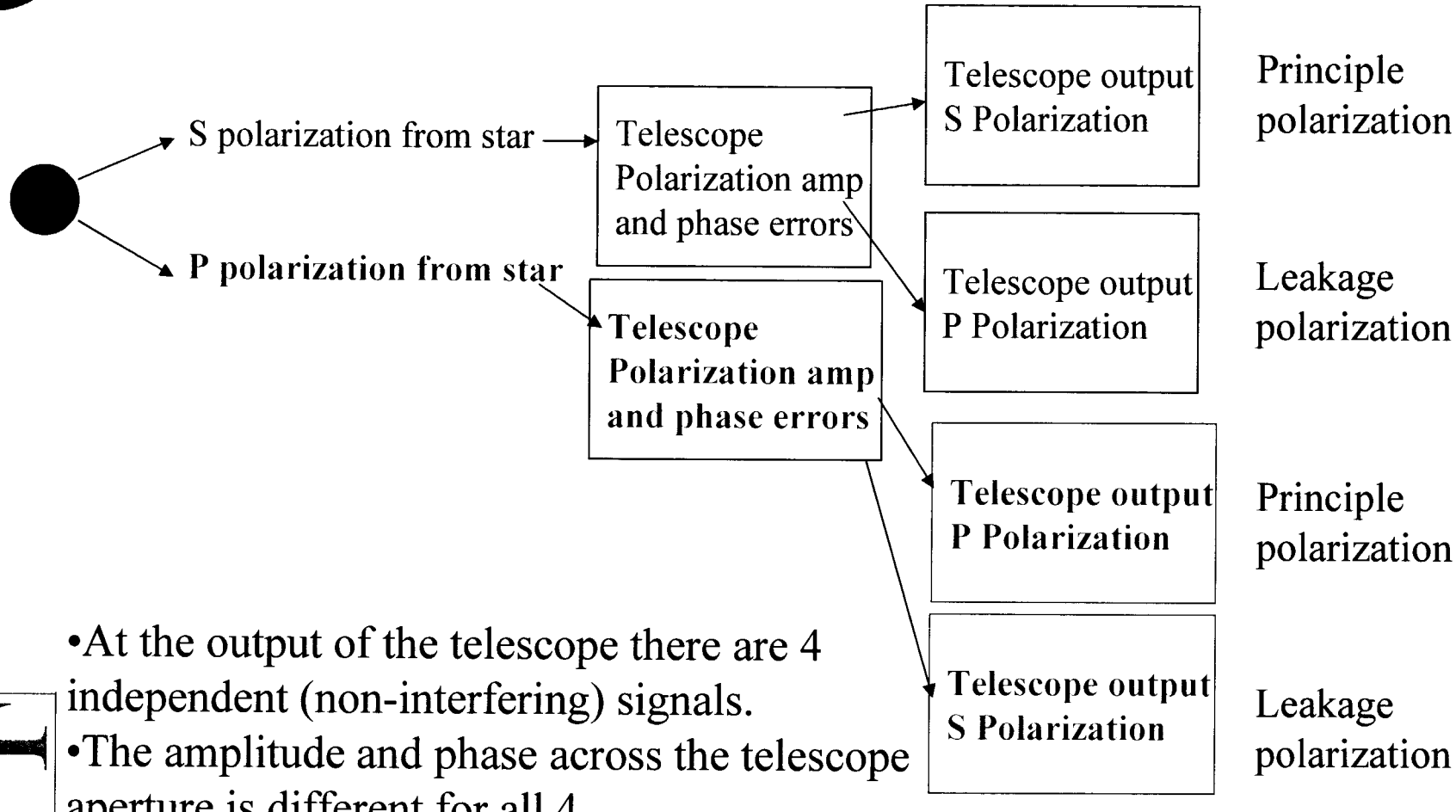
centroid box = 9x9, estimated spacing = 126.200
average fiber spacing = 126.552um rms_x= 2.498um , rms_y= 2.184um, rms= 3.318um

Latest Result from Improved 2nd Generation Fiber Array

- Array Image
  - Conventional SMF array
  - (non polished)
- Regularity Measurement



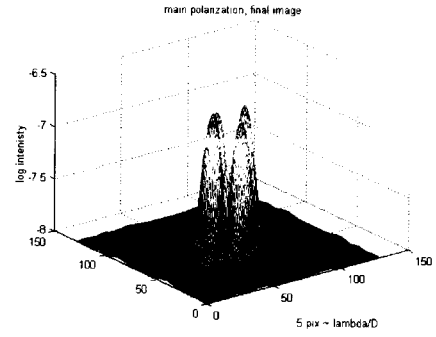
How Serious is Polarization for Coronagraphs?

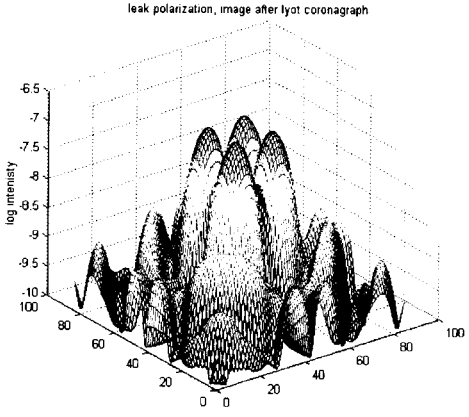


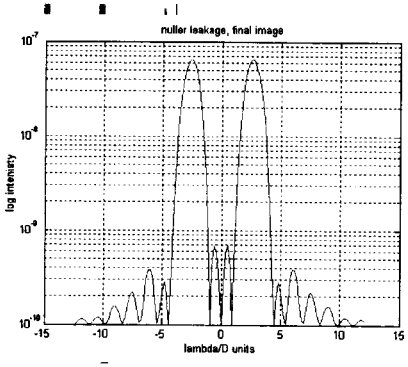
- At the output of the telescope there are 4 independent (non-interfering) signals.
- The amplitude and phase across the telescope aperture is different for all 4.
- A deformable mirror can only correct 1 wavefront.

The requirement to accommodate polarization is a potentially serious issue.

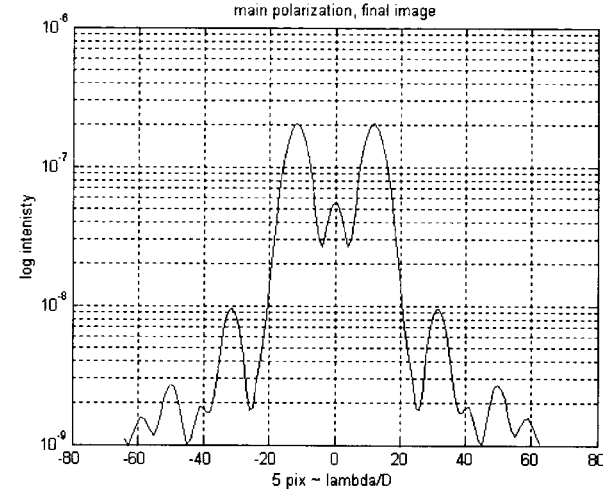
Stellar Leakage from Polarization?



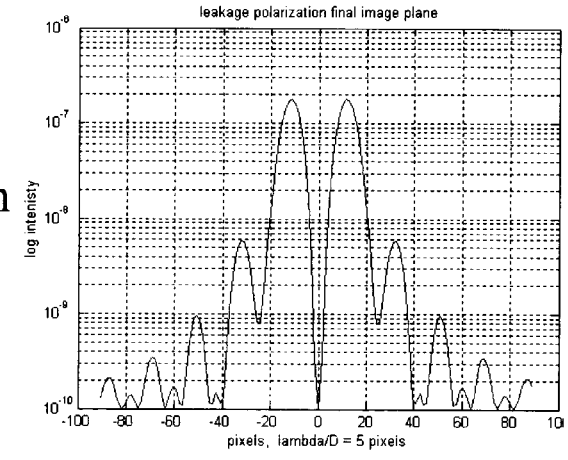




- The polarization distorted wavefronts were propagated through a simulated lyot coronagraph designed to suppress starlight to ~2e-9 at 3 λ/D
- Analysis of what polarization does to a nuller is currently underway.
  - Preliminary results in two polarizations show that the nuller, like the lyot coronagraph will not work.
  - With a post telescope polarizer, only the leakage term is important and the nuller seems to be slightly better than the lyot coronagraph, 6e-8 vs 2e-7 at 3 λ/D.



This graph says a polarizer is needed "after" the telescope



This graph says a polarizer is needed "before" the telescope as well.

Mission

Summary

- **Single Aperture Telescope with a Visible Nulling Coronagraph Capable of Imaging and Spectroscopy of Planets**
  - **Jupiter-like planets (D~1.2m)**
  - **Earth-like Planets (D~4m)**
  - **Resolution scales with shear (up to the diameter of telescope)**
- **Mission Concept and Instrument Defined**
- **Starlight Suppression is the Most Challenging Technology**
  - **Closed Loop Null @ 5.2×10^{-9} with Laser Metrology Demonstrated**
    - **50x from TPF goal**
  - **2 Fiber Arrays under Construction**
    - **Conventional SM Fiber and Photonic Crystal Fiber**

Future Work

- **Near Term**
  - **Deep White Light Nulls under Laser Metrology**
    - **$1x10^{-6}$goal**
      - **10x from TPF goal**
  - **Single Mode Coherent Fiber Array Demonstration**
    - **Fiber Uniformity Measurement Gauge**
    - **100 Fiber Array Goal**
  - **Characterization of DM Stroke Accuracy and Stability**
  - **Advanced Polarization Modeling**
- **Long Term Experiments:**
  - **Multiple Channel Null Demonstration**
    - **Use of DM to control amplitude and phase**
  - **Integration of Nuller and SMF Array in Test Bed System Demonstration on Test Bed**