The Visible Nulling Coronagraph--Progress Toward 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 this in a space mission, present latest results of laboratory measurements demonstrating achievable null depth and component development, and discuss future key technical milestones.

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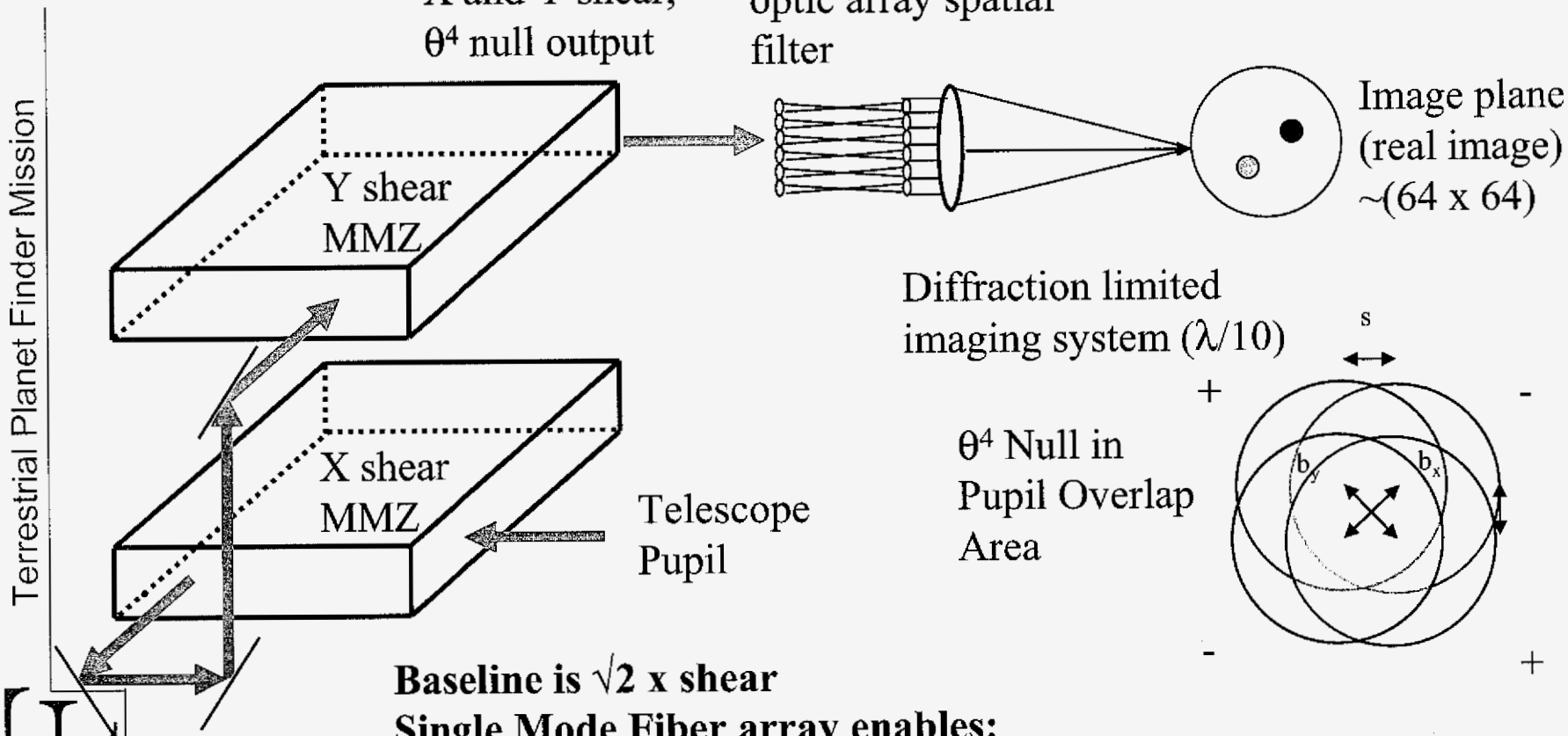
Visible Nulling System Concept



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Turning/Rotation Mirrors

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**

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Why Another Coronagraph Concept?

- A modest sized aperture telescope can resolve an extra-solar planet and collect sufficeint amount of light
  - 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)
- Nulling interferometer/coronagraph belongs in a class of small inner working distance devices
  - Use 4~5m class telescopes (less expensive than larger telescopes).
- The nulling coronagraph is (Orders of magnitude) easier to control scattered light, at the required constrast of 10^{-10} per airy spot
  - Amplitude, Phase, Spectral Bandwidth, and Polarization Controls
  - Concept Heritage from:
    - Bracewell and McPhie (Nulling Interferometer)
    - Shao (Hubble Extra-Solar Planet Imaging)
    - Angel, Angel & Woolf (Large Telescopes, Nulling Interferometers)
  - The Nulling Interferometer is the Enabling Technology
    - Heritage from SIM Nulling
  - The Fiber-optic Spatial Filter is Enhancing Technology
    - Uses Telecom & AO components

Imaging with a Nulling Interferometer

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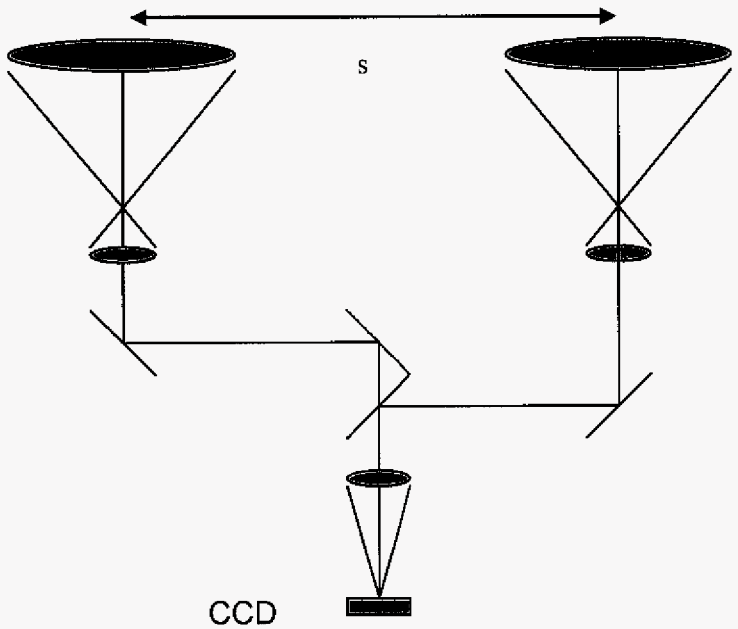

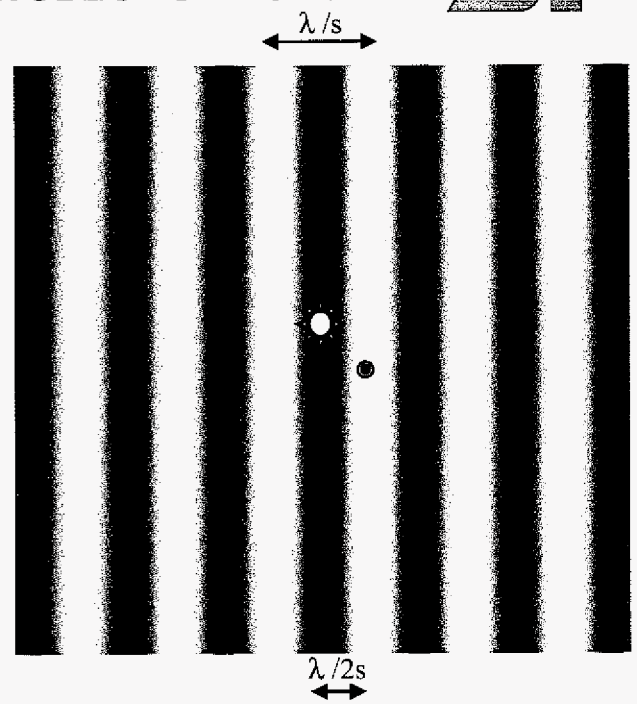

Null Transmission Pattern on the sky.
(Star is at the center)

- 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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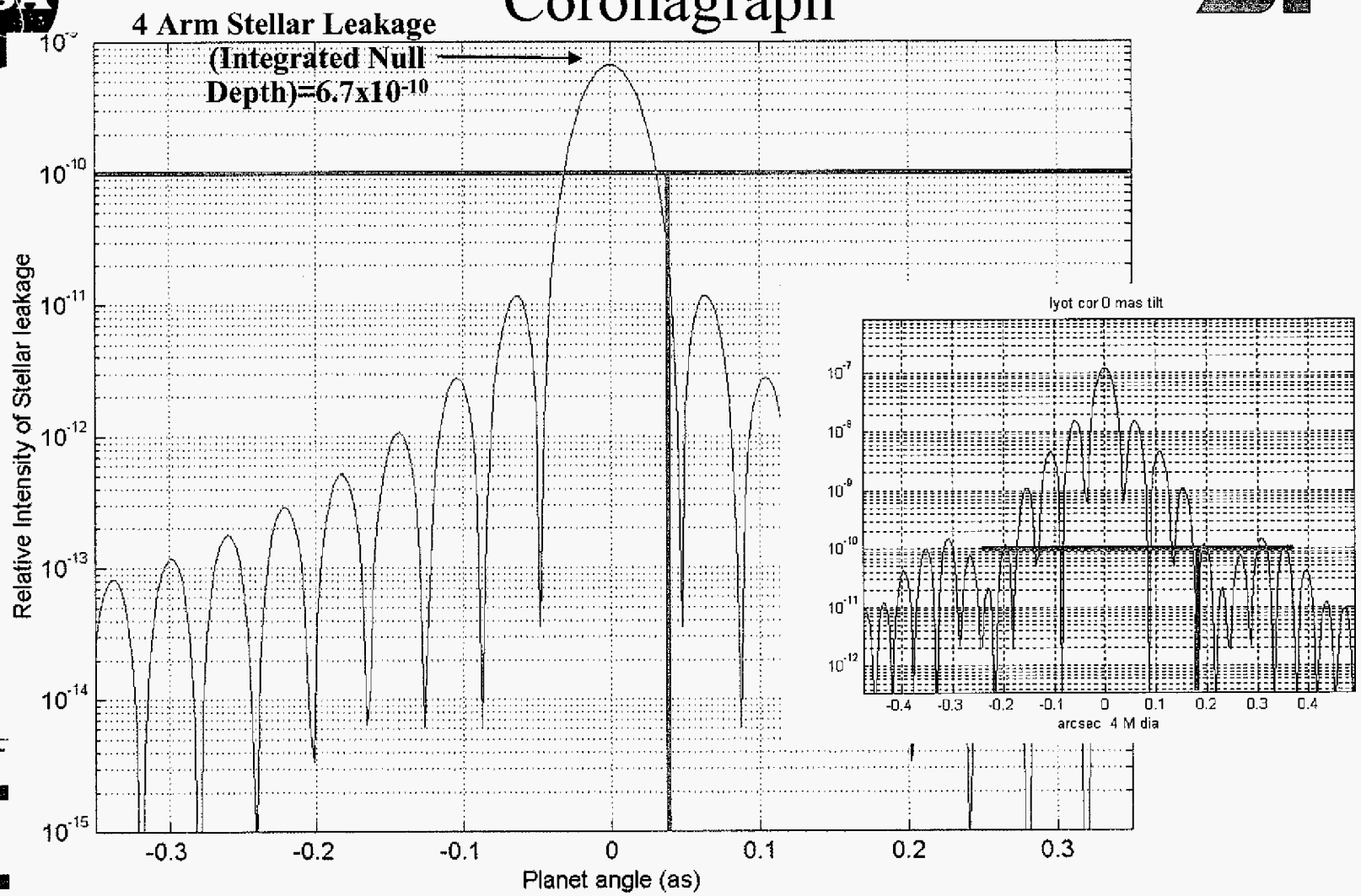
Ideal performance of Visible Nulling Coronagraph



- Four-arm interferometer leakage below 10^{-10} at $\theta \sim \lambda/D$

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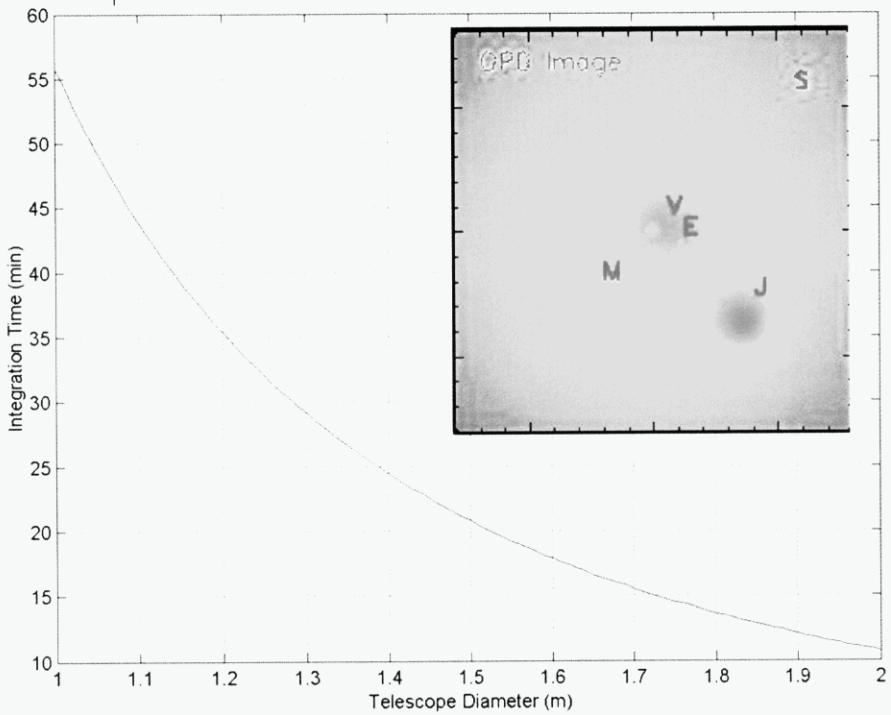
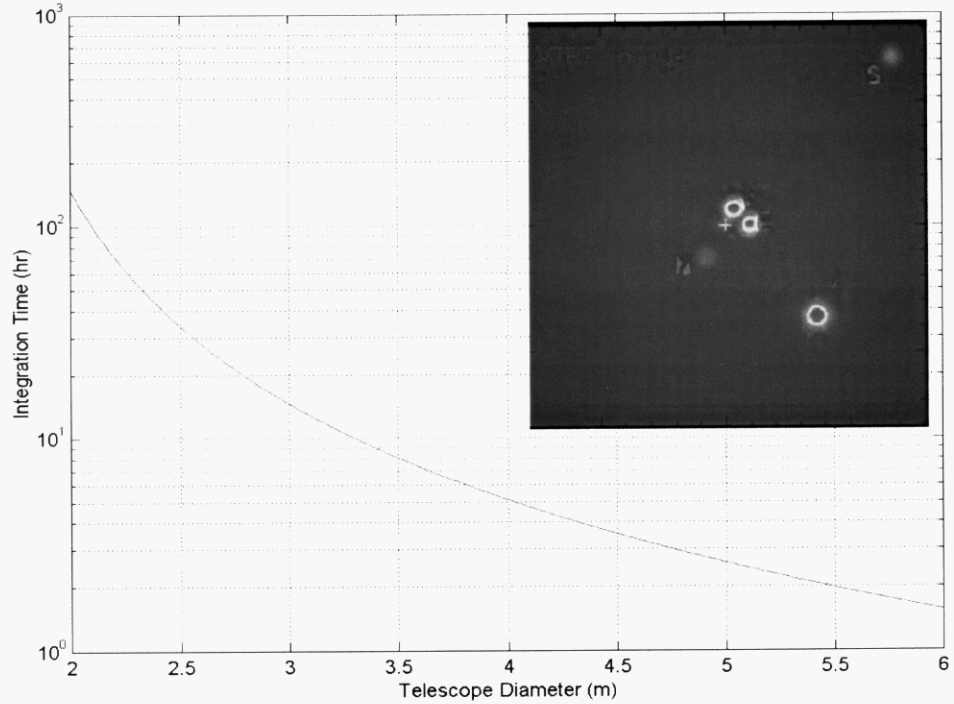
Imaging Simulations (Velusamy)
Integration Time for SNR=5

Simulated image of our solar system at 10pc



1.5m telescope



4.0m telescope

- Nulling Coronagraph changes requirement that large apertures are required for TPF science

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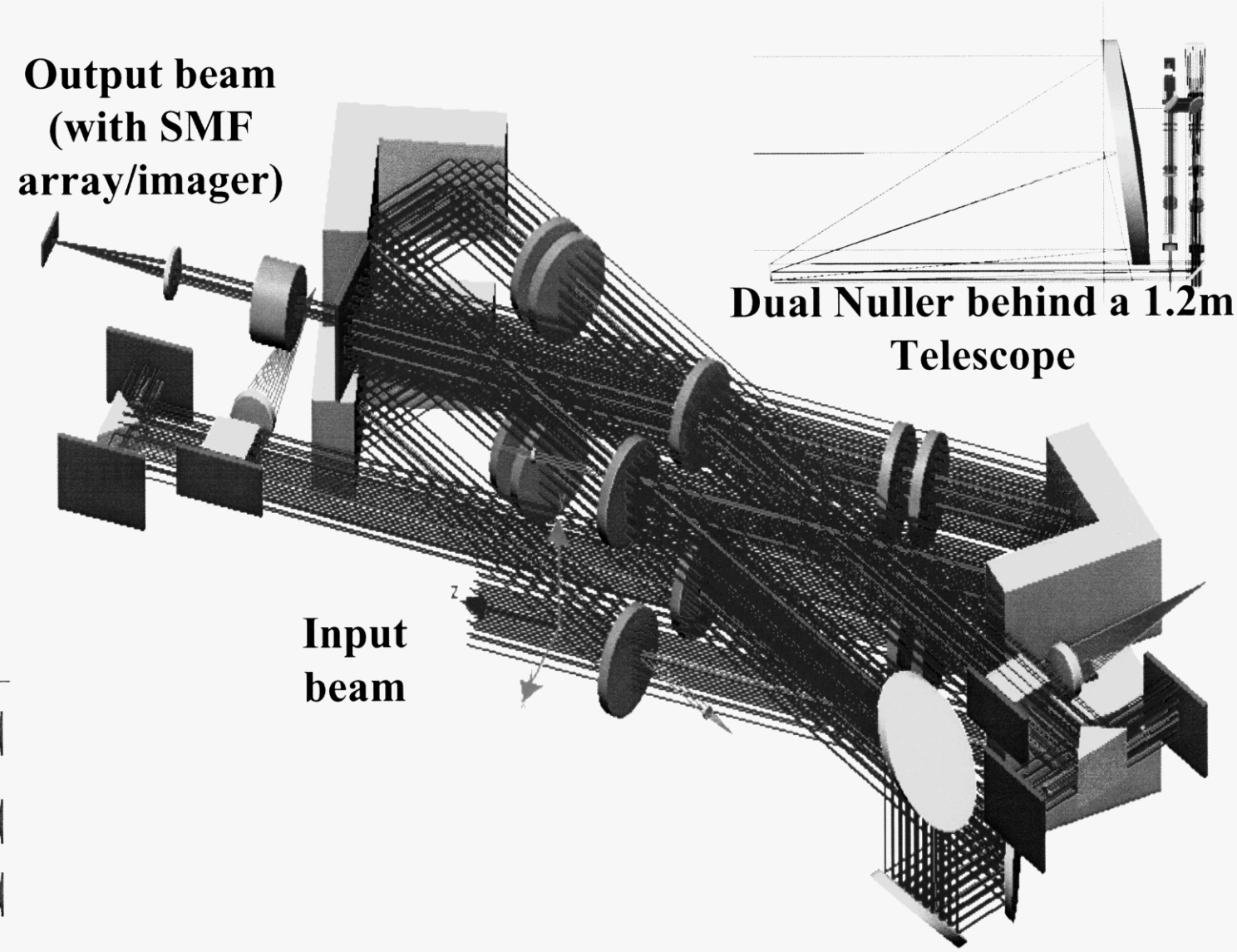
Dual Nuller Flight Instrument Configuration



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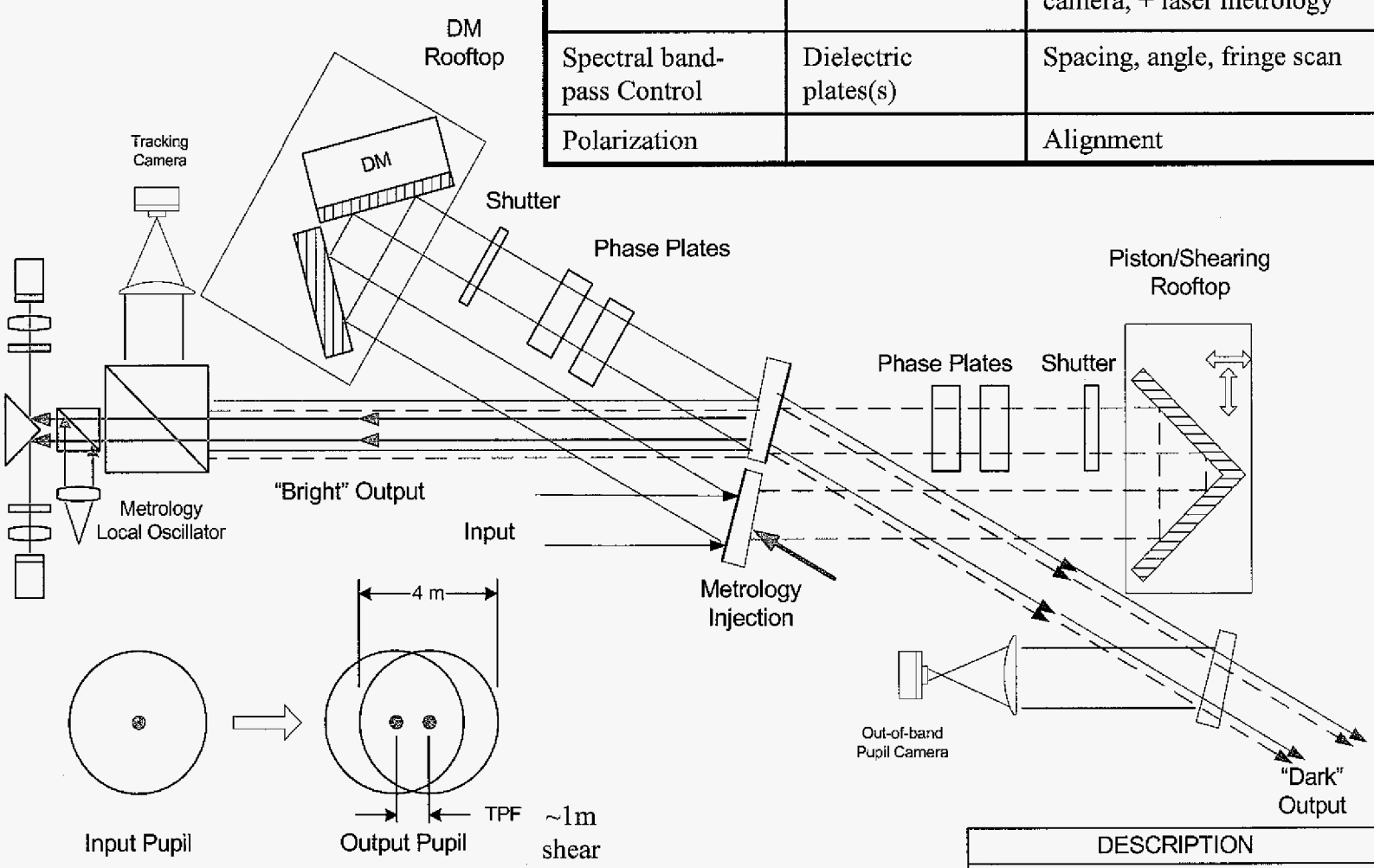
Nuller #1 with Control Points

Amplitude Control	Tip/Tilt	DM segment, out-of-band camera
Phase Control	Piston	DM segment, out-of-band camera, + laser metrology
Spectral band-pass Control	Dielectric plates(s)	Spacing, angle, fringe scan
Polarization		Alignment



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DESCRIPTION	
VTPF Nuller 1	
REV: A	ISSUED: 01/13/03

Proof of Concept Nulling Interferometer Demonstration (Wallace)

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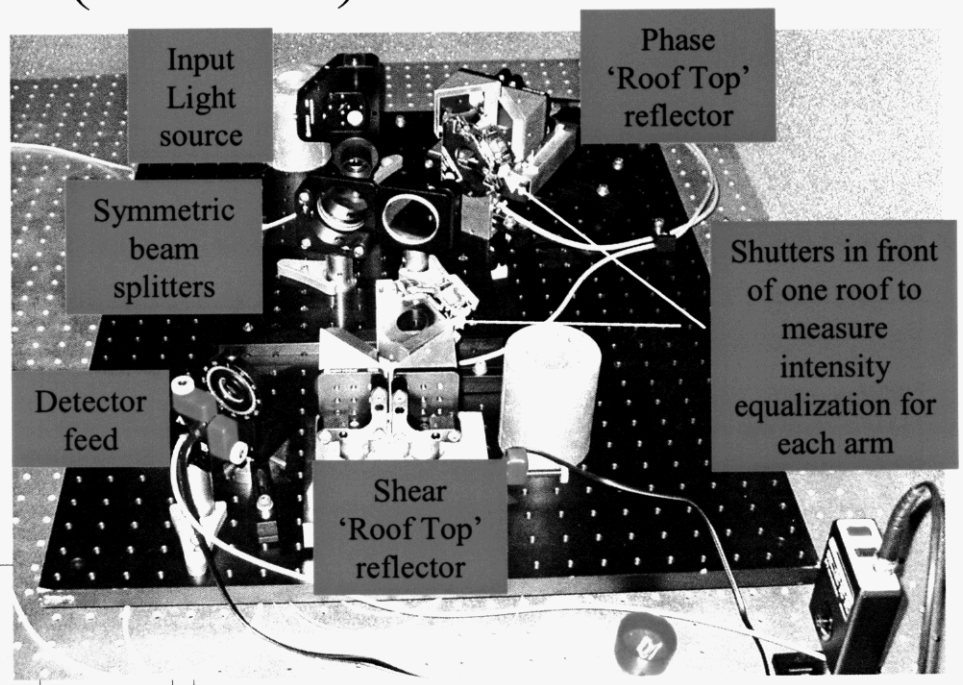
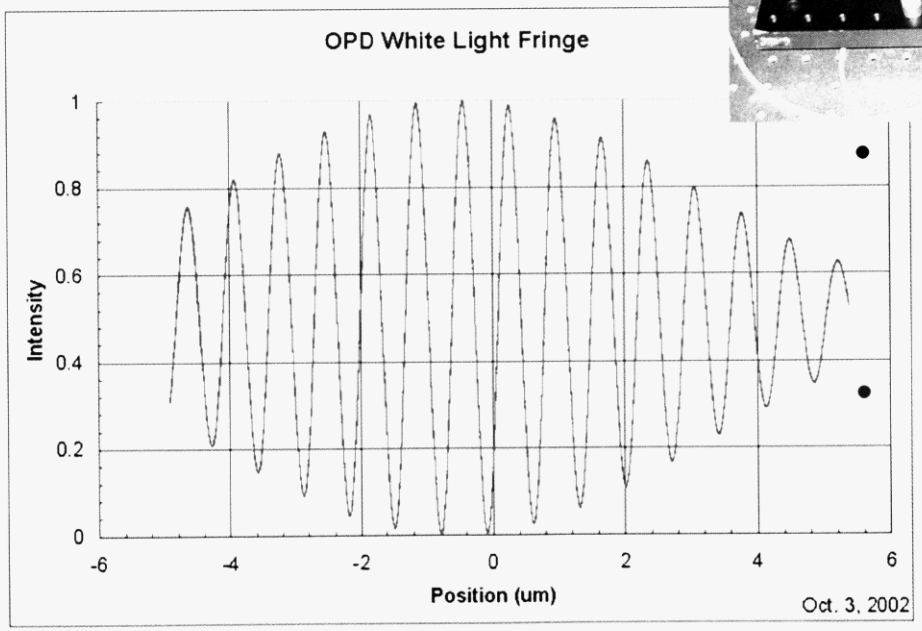
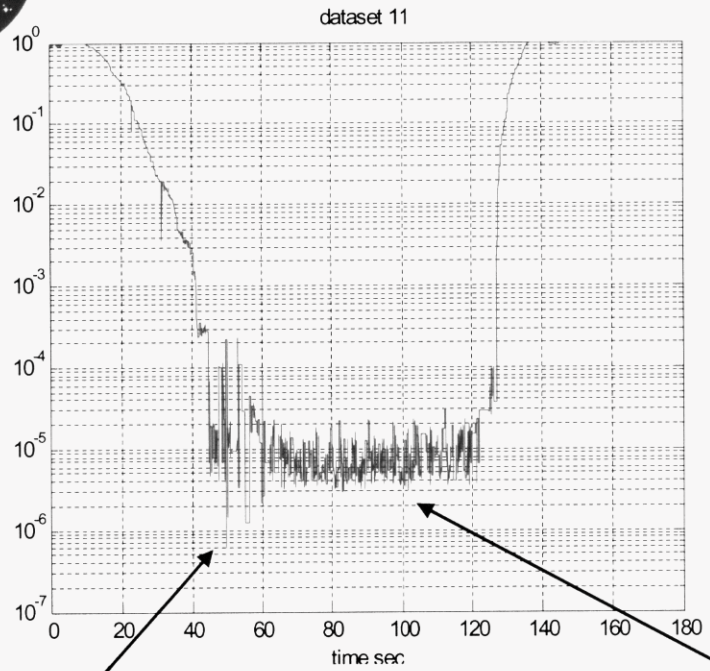


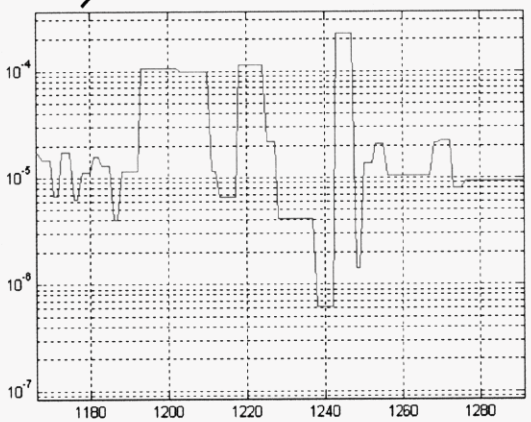


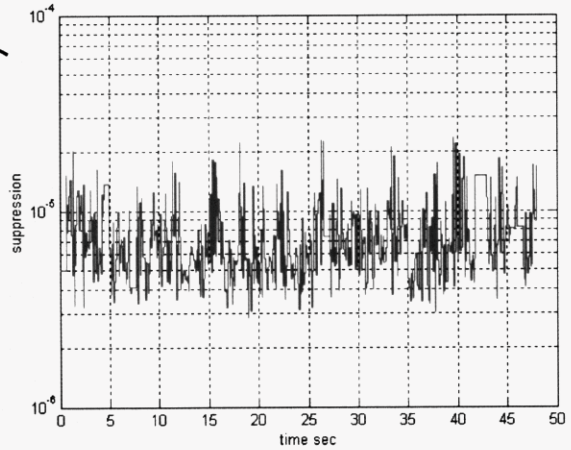
- **First Laboratory Results--White Light Fringe Scan**
  - Optical bench 'isolated' with pads and doors, otherwise ambient laboratory conditions
- **The starlight leakage only depends on the <u>amplitude and phase</u> mismatch inside the fiber.**

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"
- Proof of principle experiment prior to metrology implementation





- Best transient null 6×10^{-7} (6×10^{-10} per airy spot), 40msec sampling

- Sustained null, Average leakage 7×10^{-6} (7×10^{-9} per airy spot)

~ Late Nov/Early Dec 2002

TDL Terrestrial Planet Finder Mission

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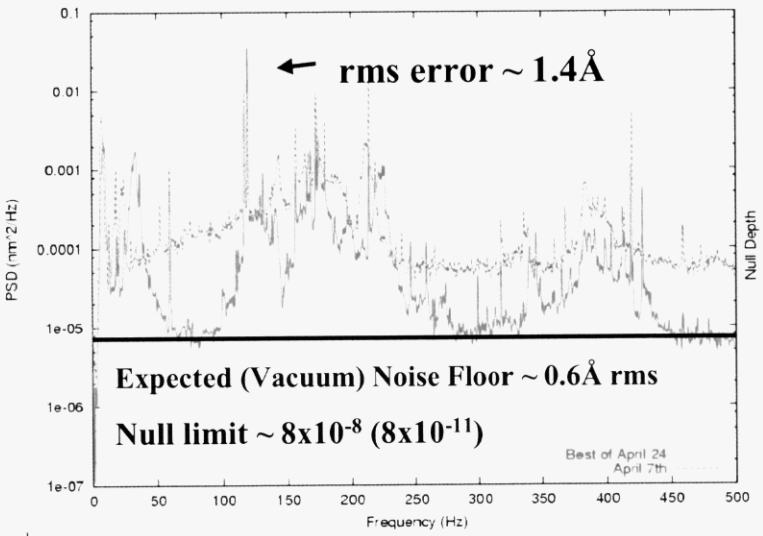
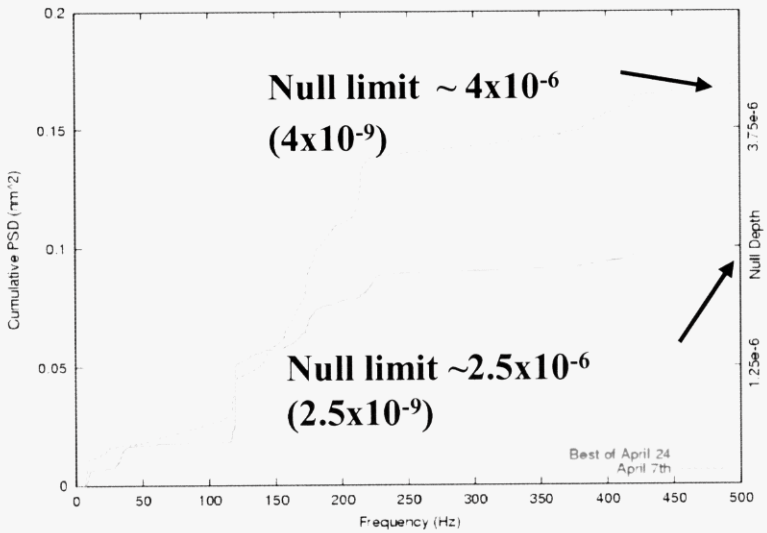
Nulling Performance under Laser Metrology

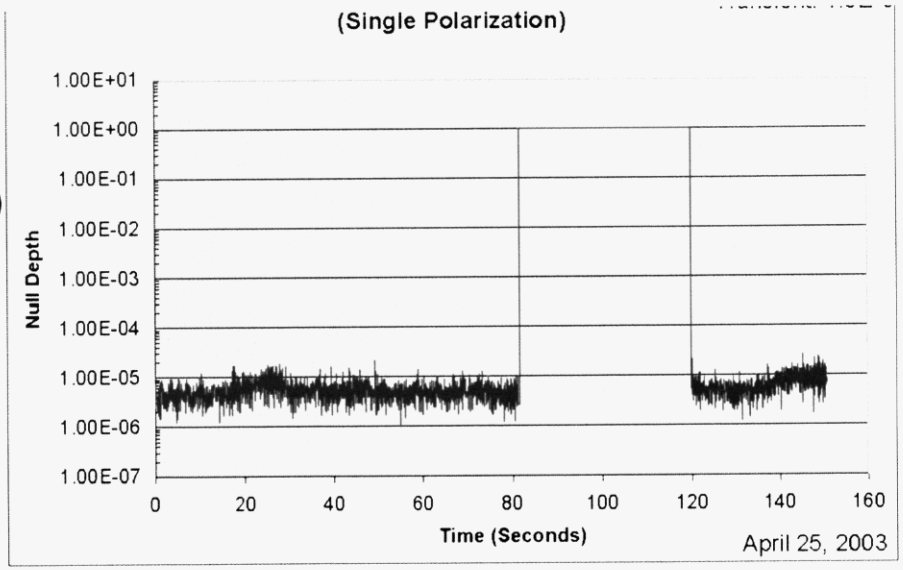
$\lambda = 635nm$





$$null\ depth \approx \frac{\sigma_\phi^2}{4}$$

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



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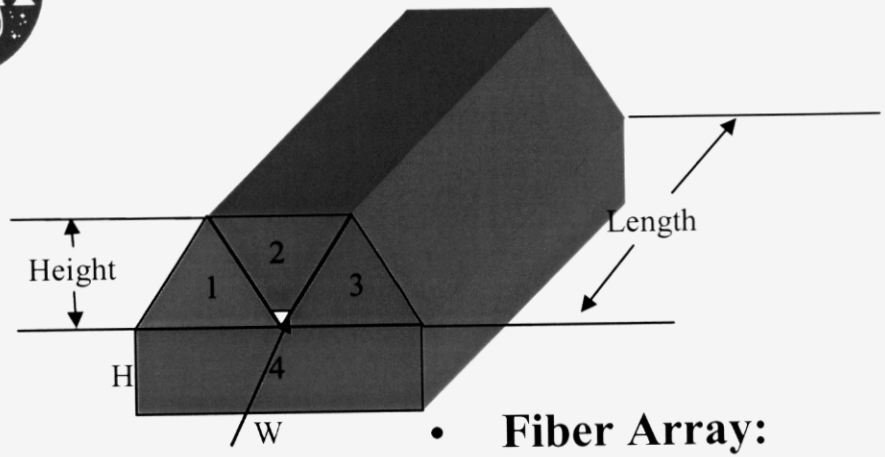
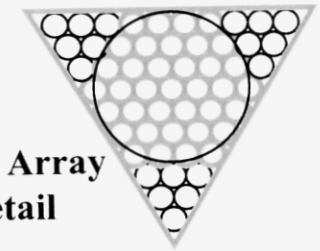
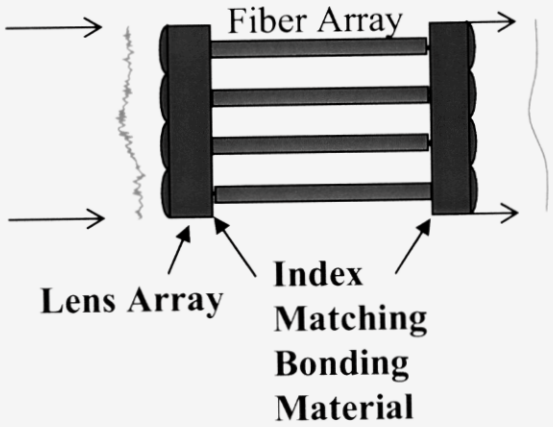
Self Assembly of Fibers in Coherent Array



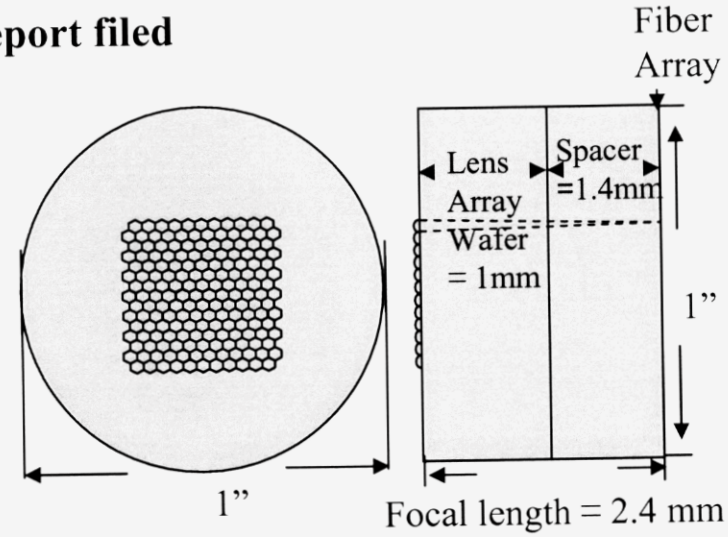


Fiber Array Detail



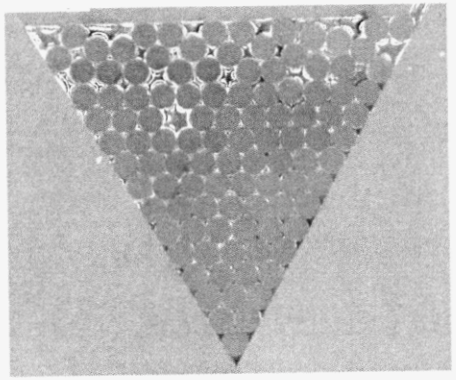
- **Fiber Array:**
  - **3 Dove prisms on rectangular slab**
  - **Prism 2 corner is cut flat to accommodate Fibers**
  - **New Technology Report filed**

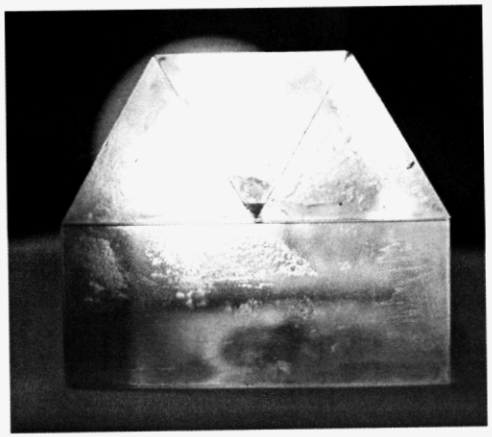
- **Lens Array**
  - **Monolithic Lens Array on thin substrate**
  - **Spacer bonded with thickness = focal length**
  - **Lens spacing 126.2μm**
  - **NA=0.048 @λ=0.632μm**

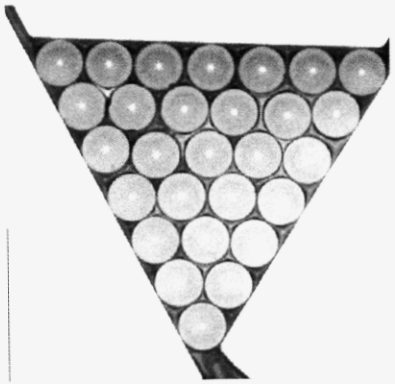


See SPIE 5170-22, Liu et. al

Single Mode Fiber Array Construction

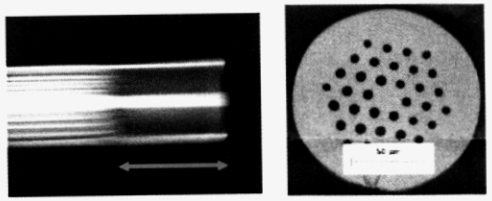






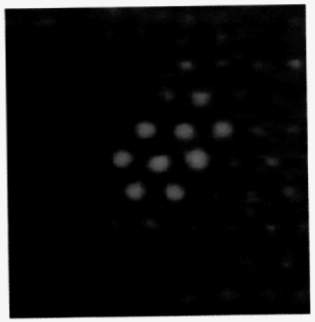
63 (Conventional) Single Mode Fibers

28 Photonic Crystal Fibers



- Far-field mode pattern from lens array coupled fibers

  λ/15rms over aperture



- 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