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The Visible Nulling Coronagraph--Architecture Definition and Technology Development

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Abstract: This paper describes the advantages of visible direct detection and spectroscopy of Earth-like extrasolar planets using a nulling coronagraph instrument behind a moderately sized single aperture space telescope. Our concept synthesizes a nulling interferometer by shearing the telescope pupil, with the resultant producing a deep null. We describe nulling configurations that also include methods to mitigate stellar leakage, such as spatial filtering by a coherent array of single mode fibers, and post-starlight suppression wavefront sensing and control. With diffraction limited telescope optics and similar quality components in the optical train (lambda/20), suppression of the starlight to 1e-10 is readily achievable. We describe key features of the architecture and analysis, present latest results of laboratory measurements demonstrating achievable null depth and component development, and discuss future key technical milestones.

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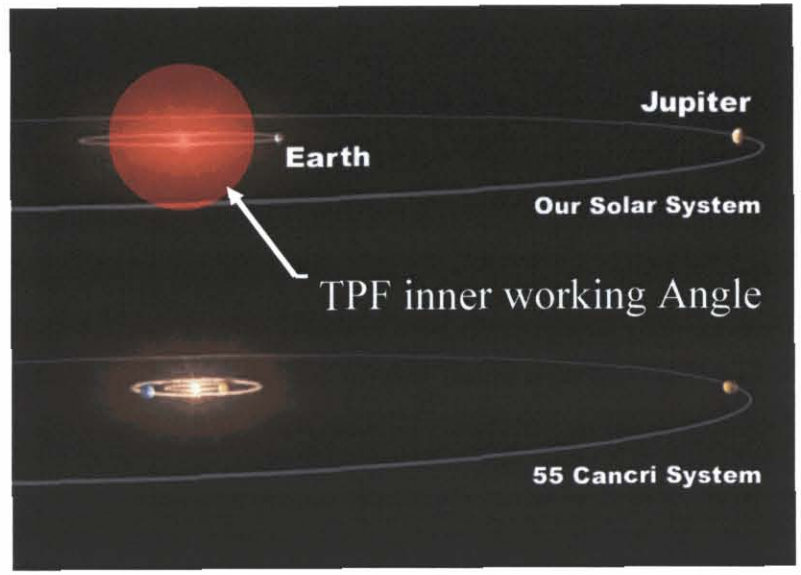
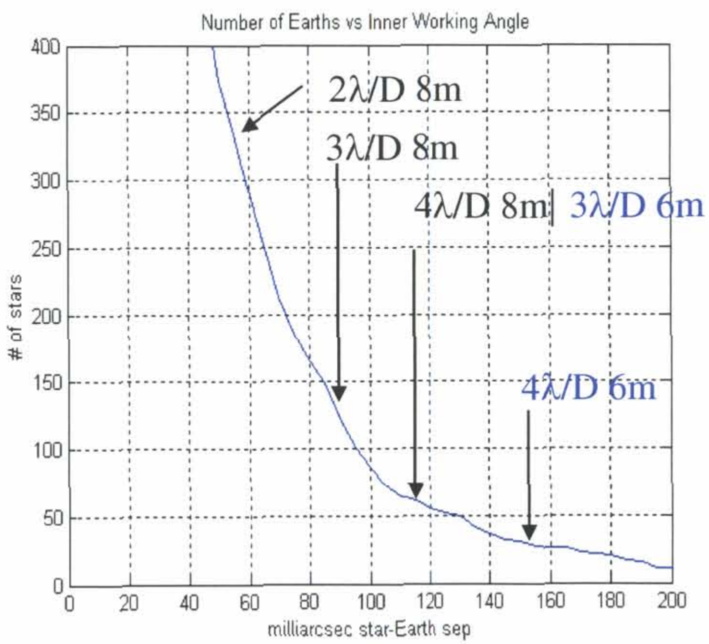
Inner Working Angle, Key to Exo-Earth Detection

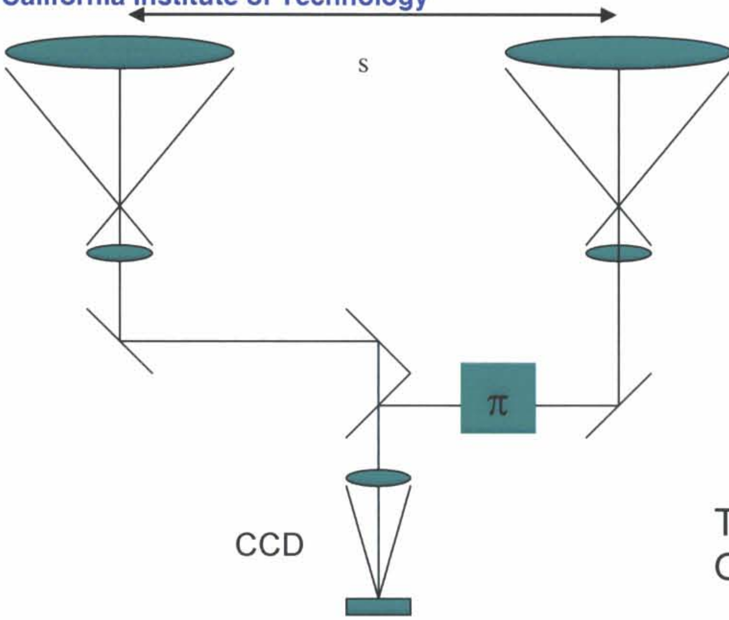
- The IWA, inner working angle is the angle inside which direct detection of a planet is not possible. (N*λ/D)
- Different types of coronagraphs have IWA with different values of N
- Next to Contrast, IWD is a driving requirement

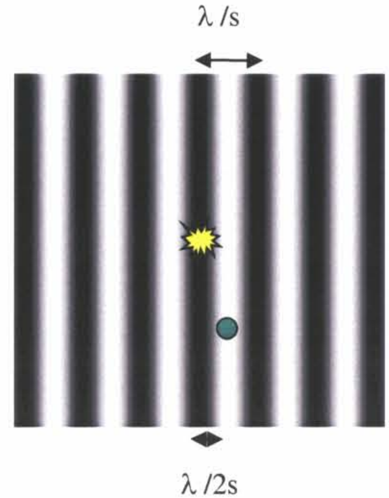




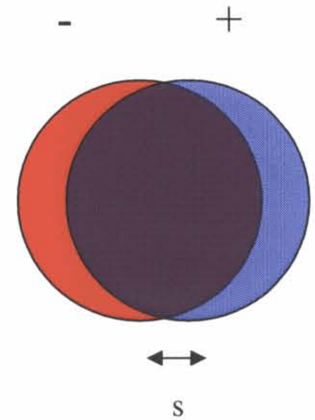
- The smaller the IWA, the greater the number of stars available for search in the habitable zone.
  - Late F,G,K, and M main sequence dwarfs
  - Habitable Zone @ 300K

Planet Detection with a Nulling Interferometer





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 or more telescopes**
  - For an Earth @ 10pc 2s~1.5m
  - **This type of interferometer is synthesized by shearing the telescope pupil**

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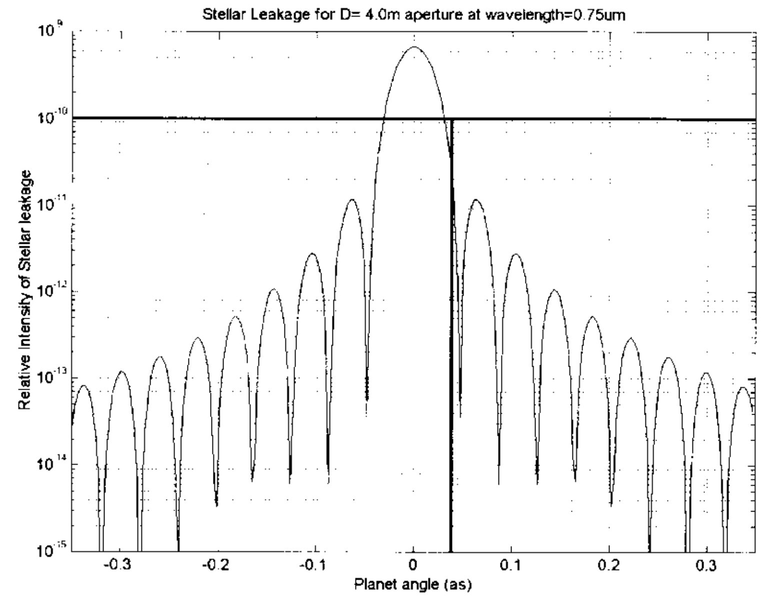
Why a Visible Nuller for TPF Coronagraph?

- **Small Inner working angle**
  - **2 λ/D with calibration**
- **Relaxed optical figure for telescope**
  - **λ/20 optics vs the requirements of 'ultra-precision' mirrors.**
- **Will ultimately prove much easier to achieve 10^{-10} suppression of starlight**
  - **Control of: Amplitude, Phase, Spectral width, Polarization, etc.**
- **Expandable to very large apertures using a segmented primary telescope.**
  - **Compatible with MEM's type deformable mirrors.**



- **θ^4 interferometer leakage below 10^{-10} at θ~λ/D**

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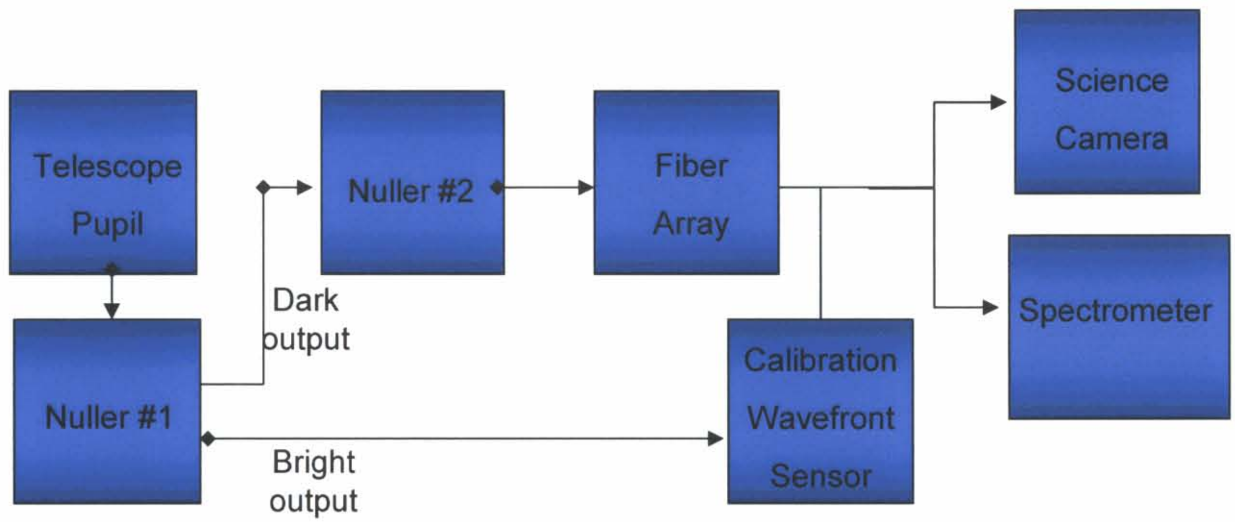
Nuller Architecture for Planet Imaging



- Yields θ^4 null

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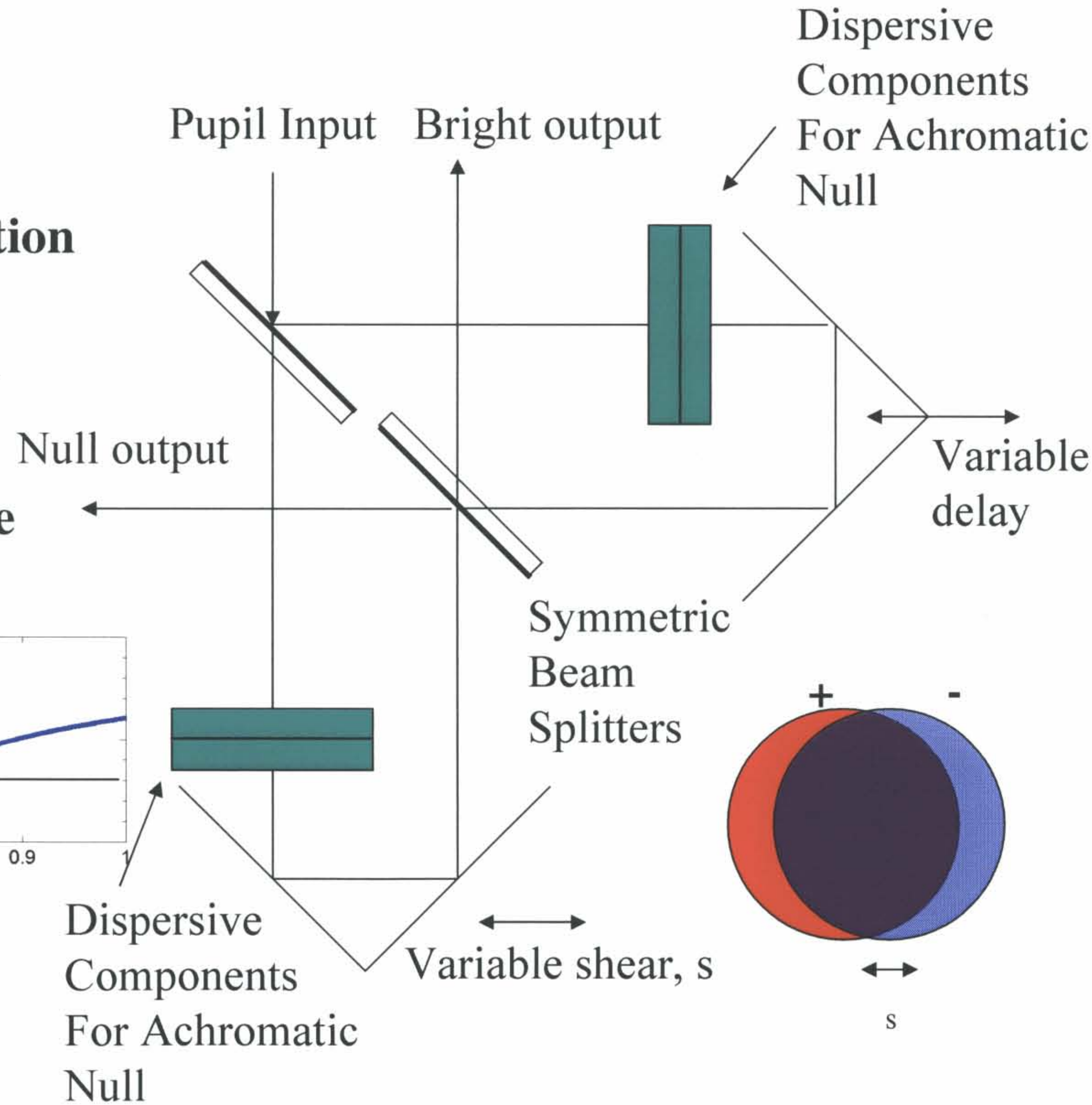
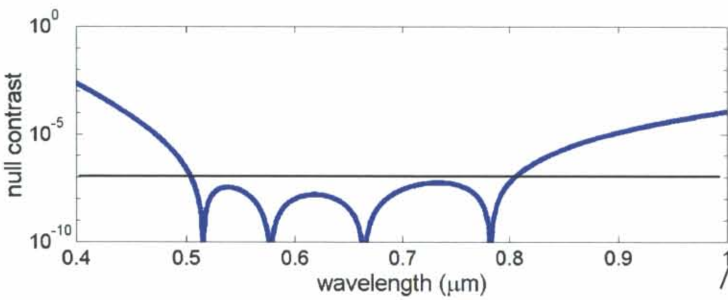
Achromatic Nulling Interferometer

- **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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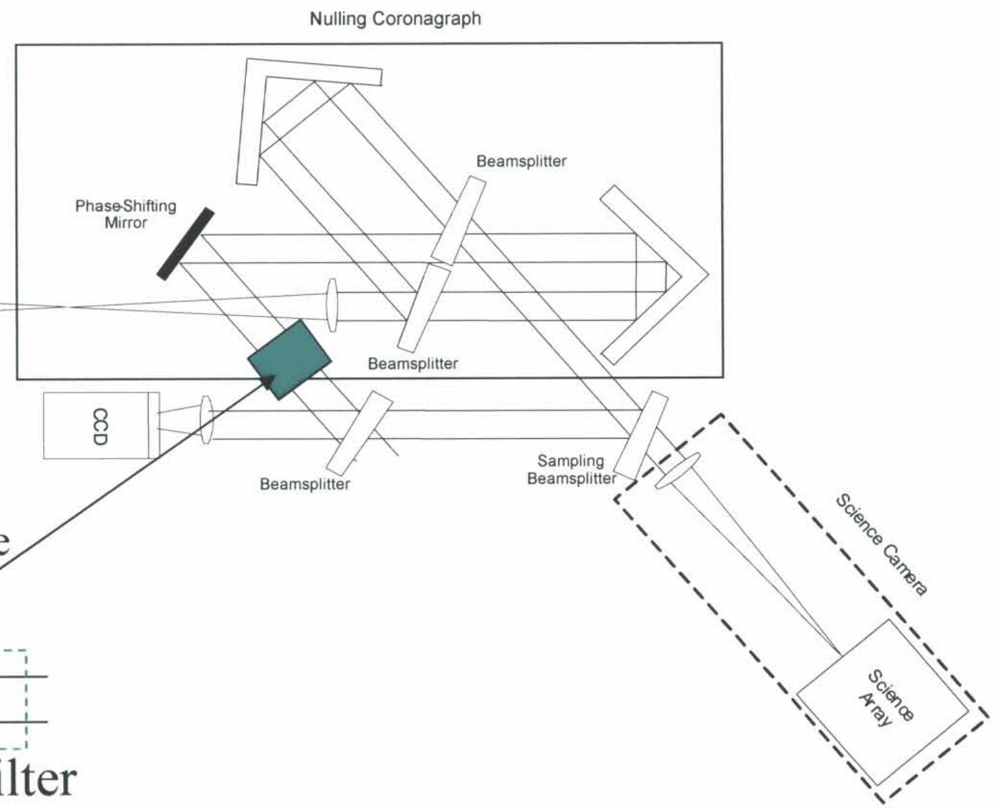
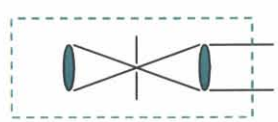
PSF Calibration: Separating the Starlight Speckles from the Planets

- **A high contrast imaging system for extra-solar planet detection requires a calibration to combat the effects of post starlight suppression errors**
  - How can you tell the difference between starlight speckles and planet light?
  - By using the coherence of starlight and property that the star light and planet light are incoherent with each other.

•Spatially filter the starlight from the bright output of the nuller.
•Interfere it with the output from the nuller (after fiber bundle).
  •This measures the amplitude and phase of the light in the speckle pattern.
•The PSF (starlight speckle pattern) is estimated by the Fourier transform of the measured amplitude and phase
•Subtract psf from science image to remove speckles





Spatial filter

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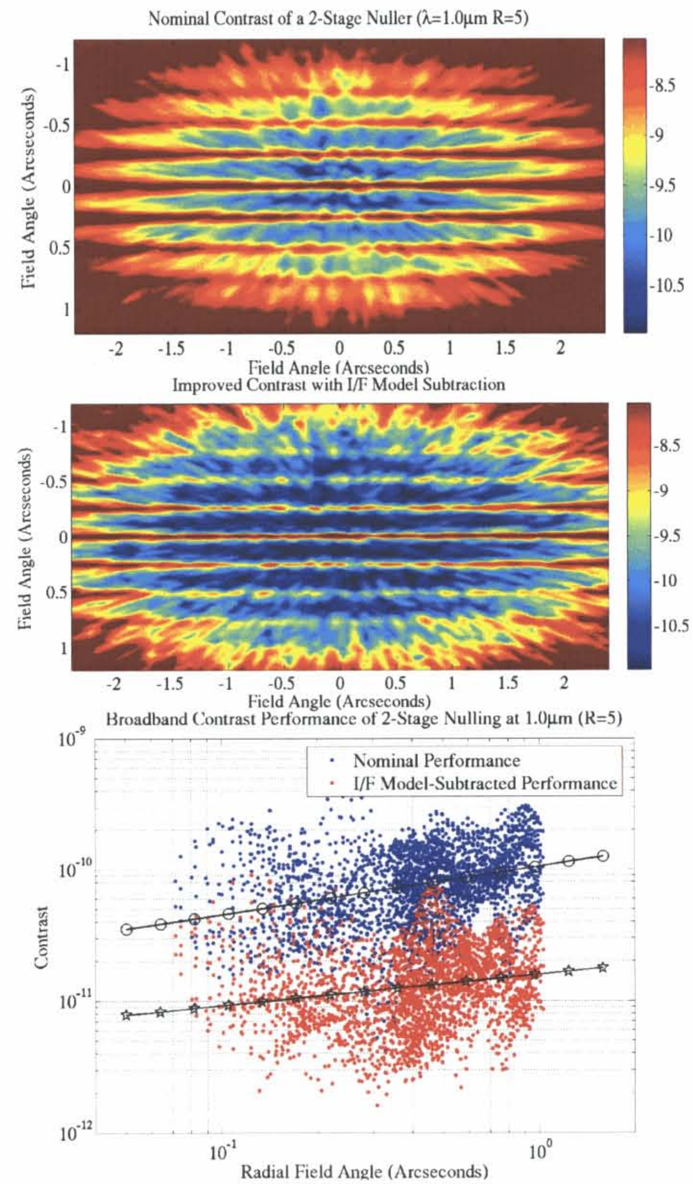
Post Starlight suppression wavefront sensing

- **θ^4 nuller**
- **Shot noise, Detector noise, pixelization included**
- **Contrast improvement α integration time$^{-1/3}$**



- Reference: Shao et. al. Session XIV

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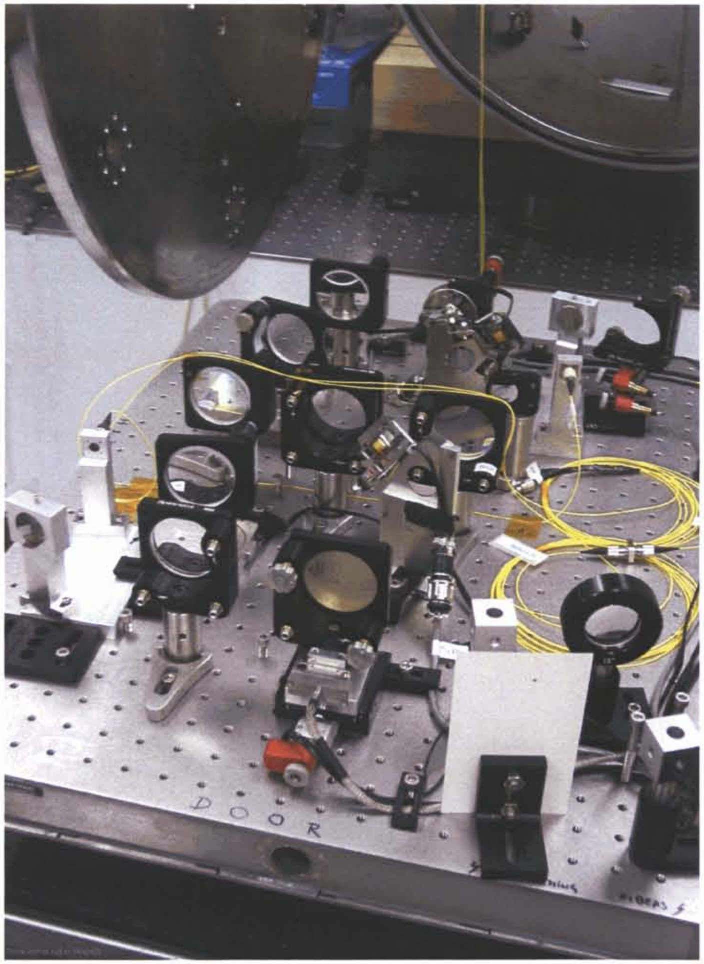
Status of Nulling Experiments

- **Prior to 2005, experiment was conducted on an optical table**
- **Since May nuller moved into the vacuum chamber**
- **To date, experiments have been run at 1 atm, with the door shut**



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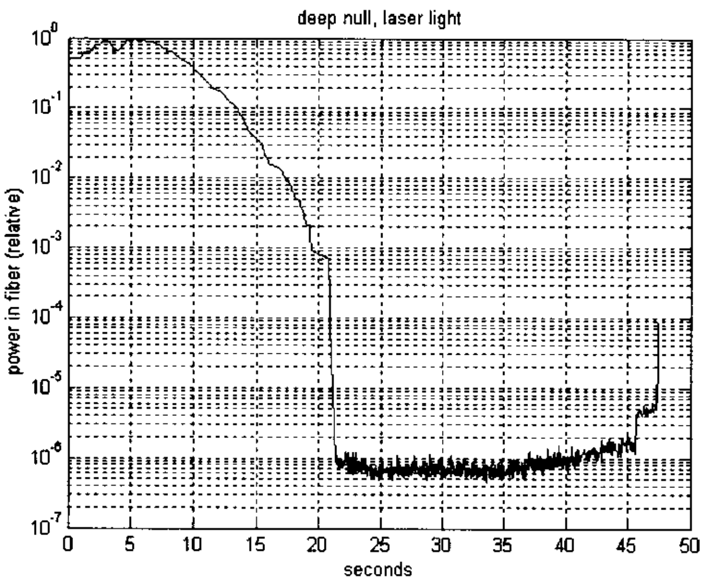
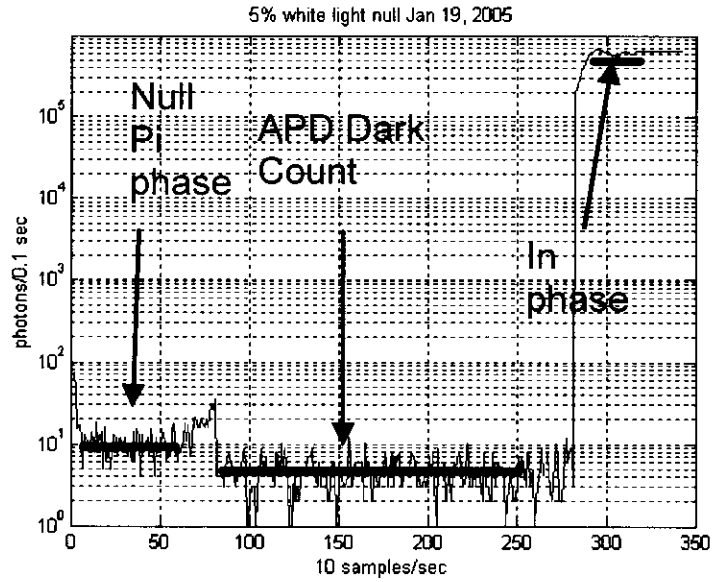
Progress in Demonstrating Deep Nulling



Laser Null: $7x10^{-7}$



White Light Null: $7x10^{-7}$

Reference: Schmidtlin et. al.
Session XII

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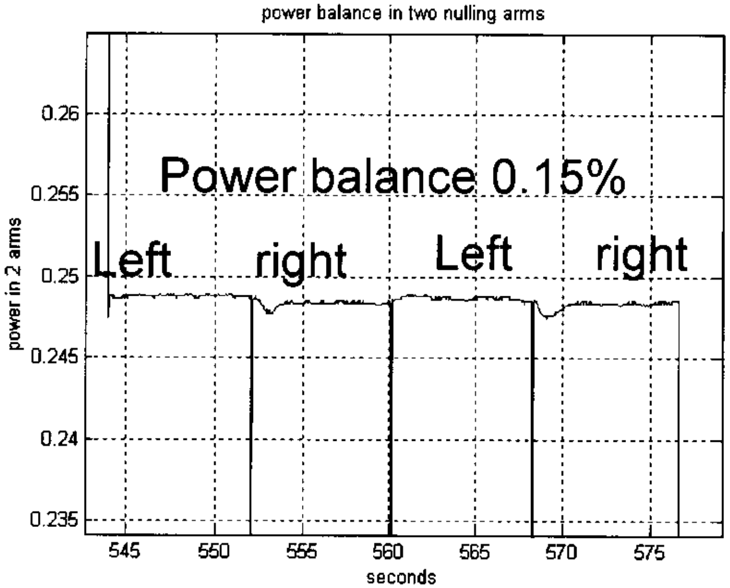
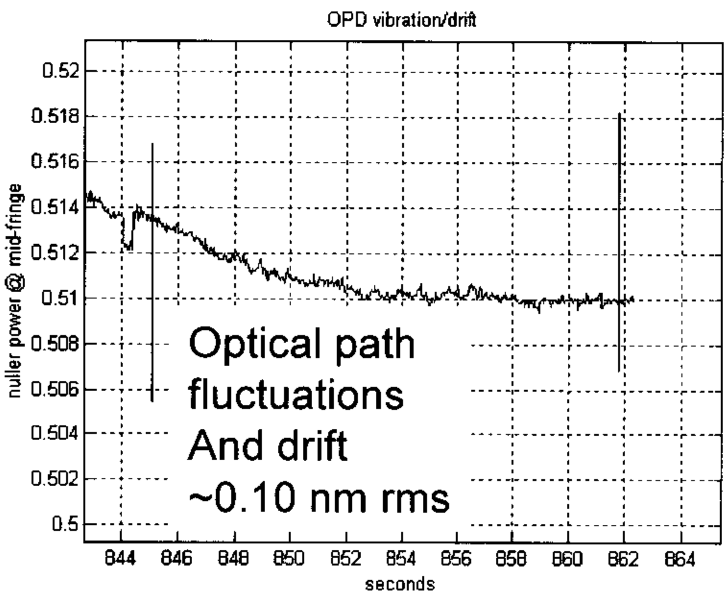
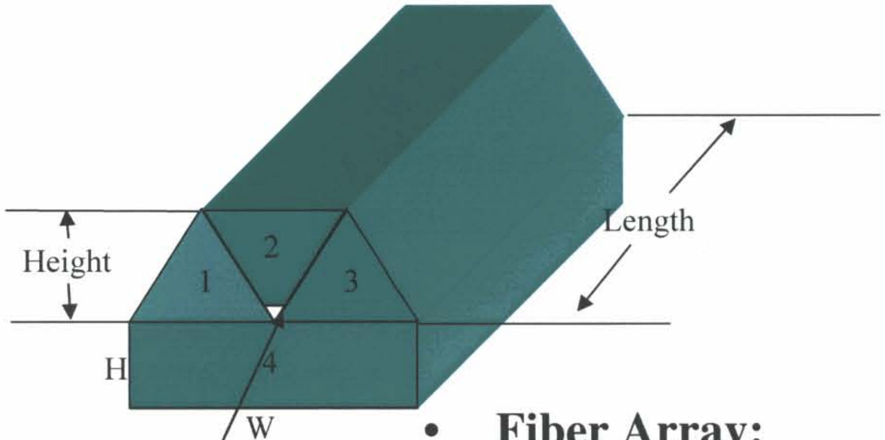
Diagnostics

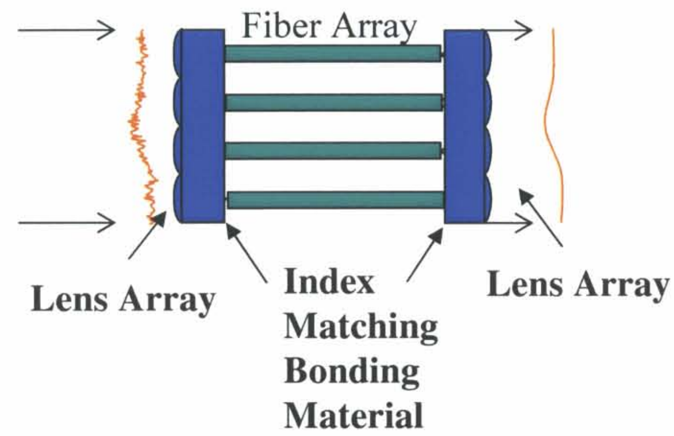


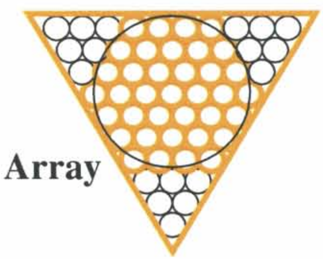


- 0.15% imbalance limits null to 2.8e-7 and 0.1 nm rms opd fluctuation limits null to 2.5e-7
  - Sum of amplitude and phase errors => ~5e-7 versus 7e-7 measured.
- Expect both amplitude and OPD stability to improve by factors of at least 3~5 when chamber is evacuated.
- Current experiment capable of 1~2e-7 nulls (1~2e10/airy spot)

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

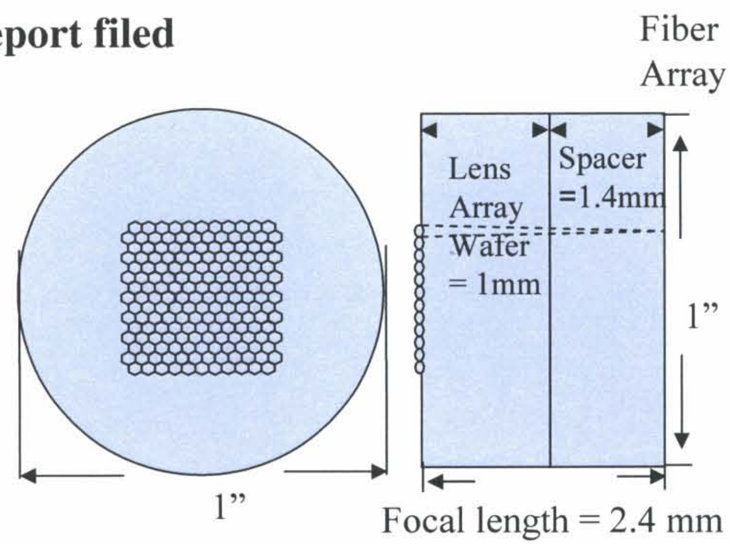






•Fiber Array Detail

- **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

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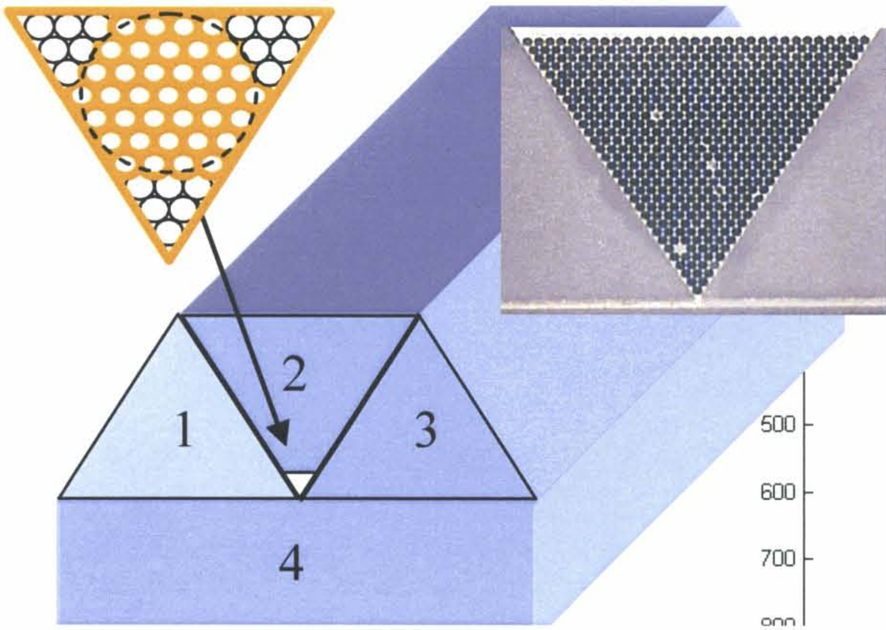
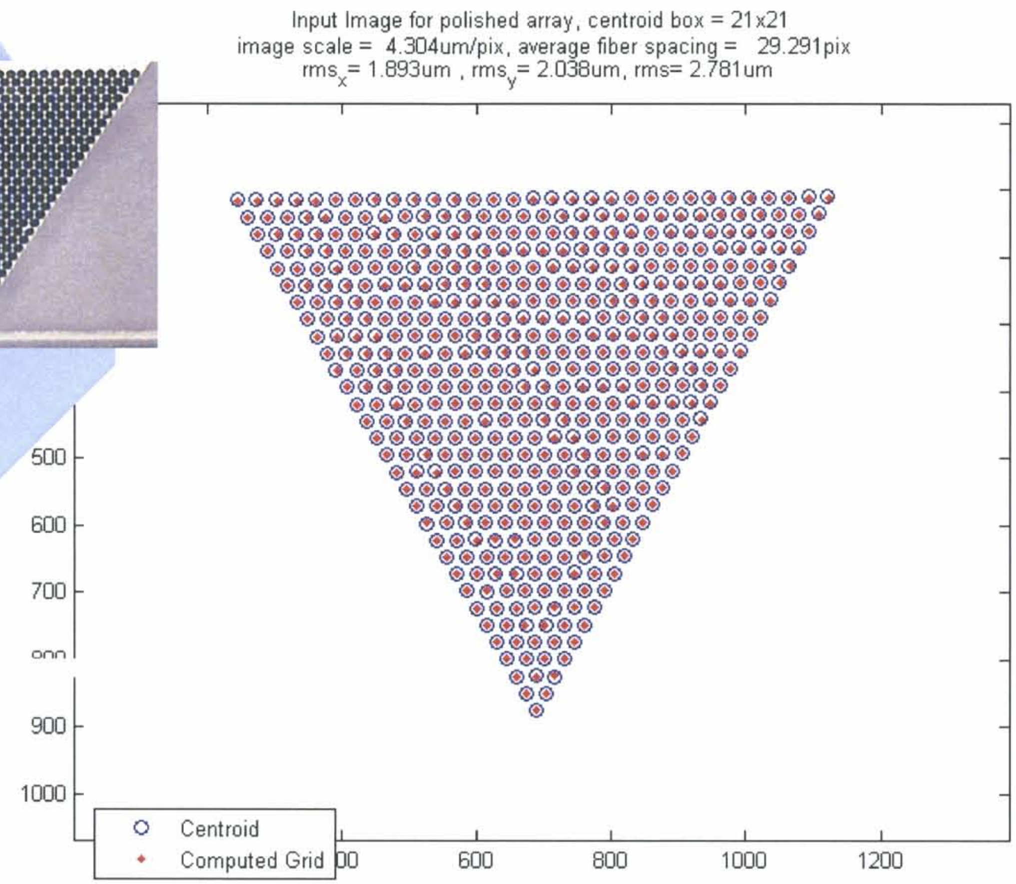
Preliminary Fiber Array Placement Accuracy
500 (331) Fiber Array





- Preliminary Measurements show 2.8μm rms position error
  - Lens arrays to be integrated with Fiber Array

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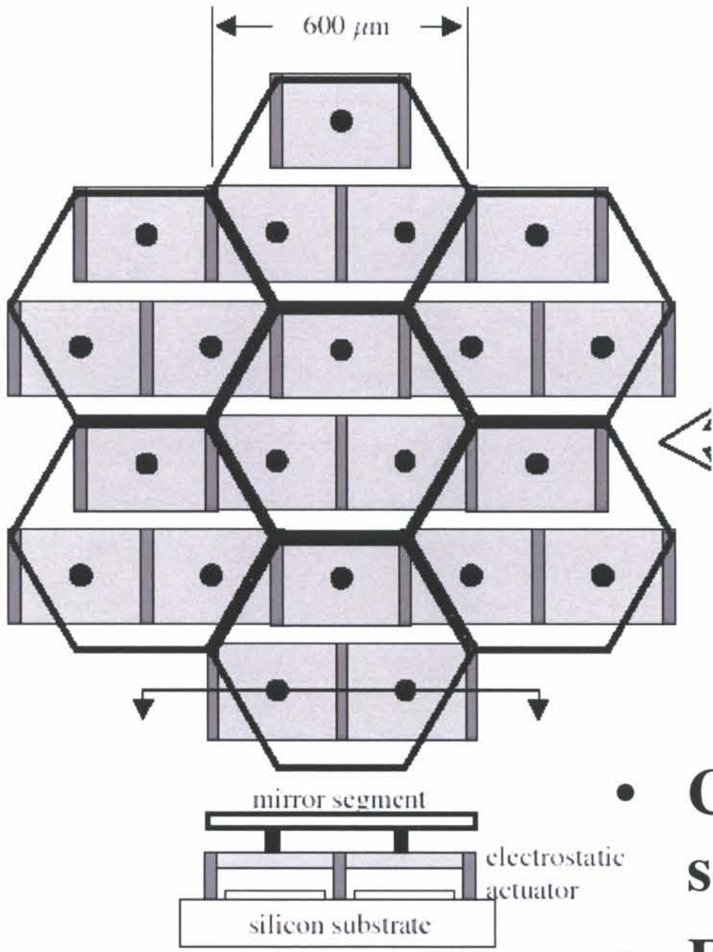
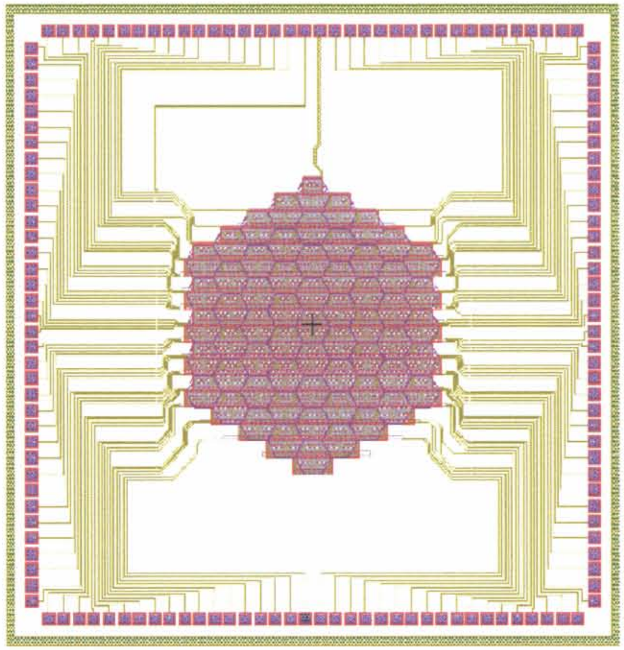
Boston University MEMS Pathfinder Deformable Mirror



61 Pixel TPF Array

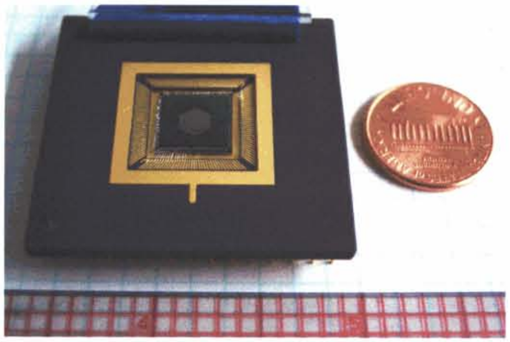


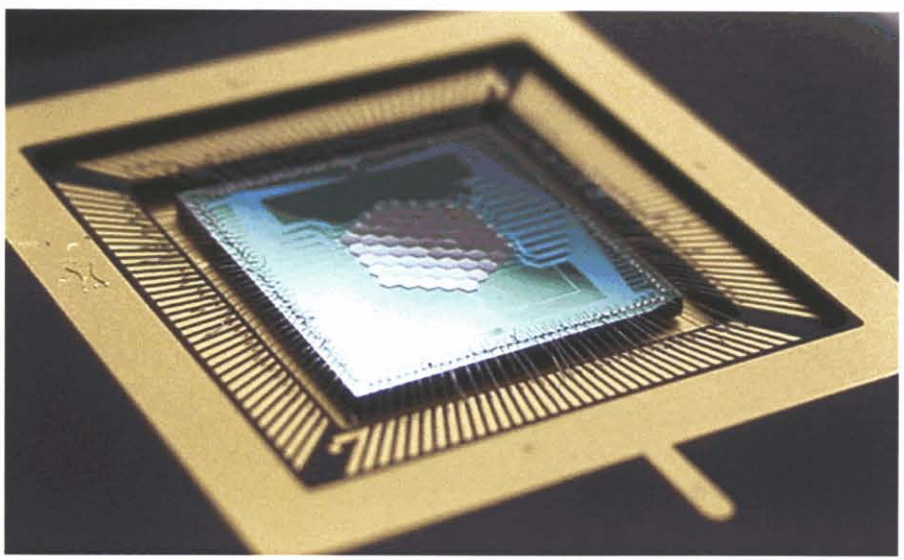
Mask designs complete: Mirror in fabrication now at MEMS silicon foundry

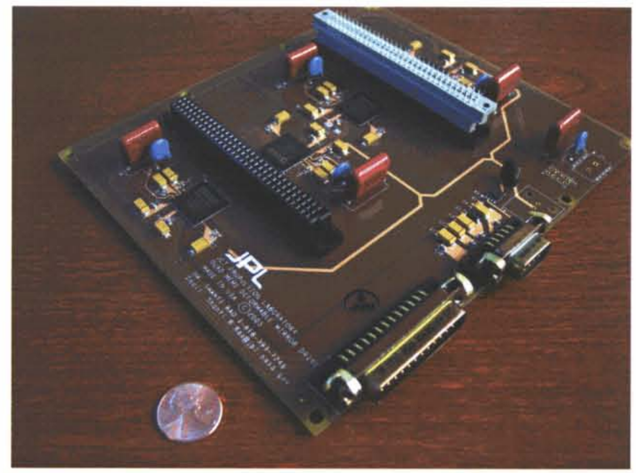
- **Current development is for a 361 segment device**
- **Future development path is for a 1000 segment DM**

BU DM + JPL Electronics

- 61 channel pathfinder DM
  - Boston University
- 128-channel D/A board







- Reference: Rao et. al. Poster #25

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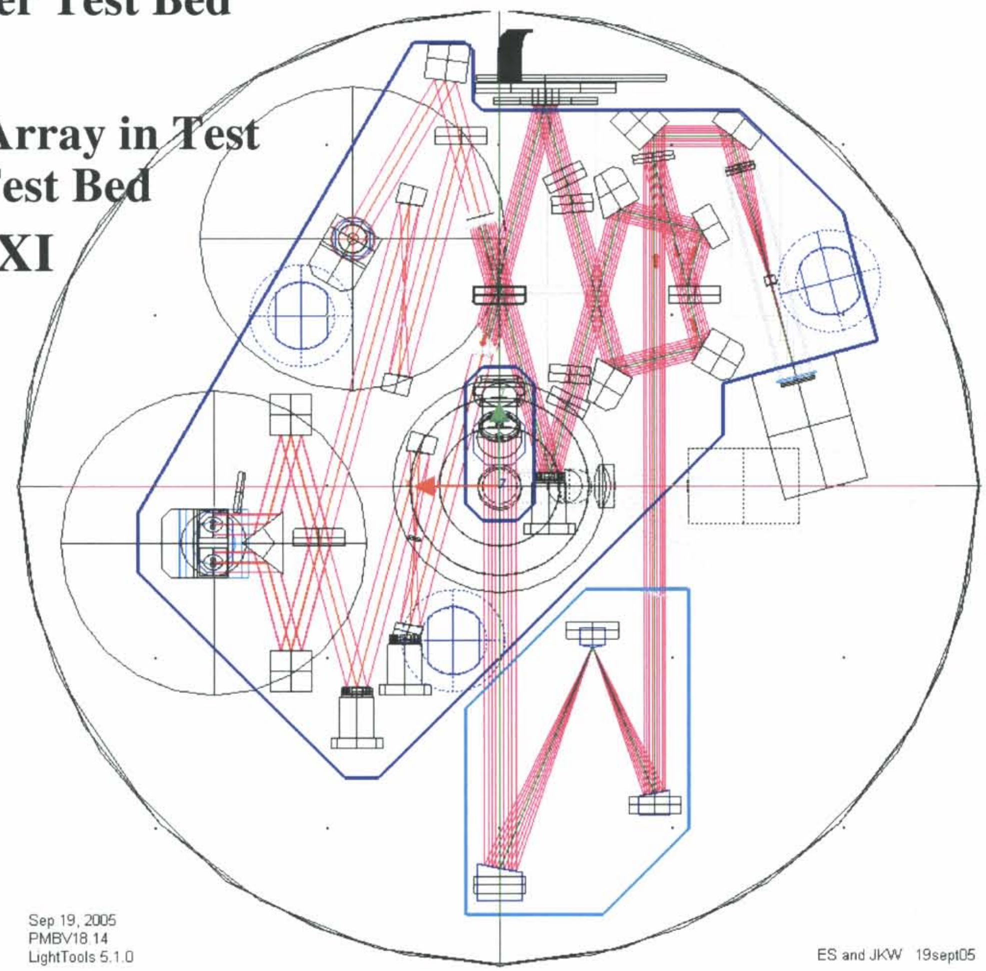
Future Work

- **Near Term**
  - **Advanced Automation of Nuller Experiment**
  - **Initial integration of Single Mode Fiber Array**
  - **Design and Modification of Nuller Test Bed**
- **Long Term Experiments:**
  - **Integration of Nuller and SMF Array in Test Bed System Demonstration on Test Bed**
- **Reference: Lyons et. al. Session XI**



- **Integrated nuller and calibration wavefront sensor design**
- **Single nuller design suitable for a future sounding rocket experiment**