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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The IWA, inner working angle is the angle inside which direct detection of a planet is not possible. \((N*\lambda/D)\)

- 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

- When the light from two pupils are combined, the output can be imaged.
  - The image is an Airy function with diameter $2.44\lambda/D$ 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 $2s \sim 1.5m$
  - This type of interferometer is synthesized by shearing the telescope pupil
Why a Visible Nuller for TPF Coronagraph?

- Small Inner working angle
  - 2 \( \lambda/D \) with calibration

- Relaxed optical figure for telescope
  - \( \lambda/20 \) 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.

- \( \theta^4 \) interferometer leakage below \( 10^{-10} \) at \( \theta \sim \lambda/D \)
Nuller Architecture for Planet Imaging

- Yields $\theta^4$ null
Achromatic Nulling Interferometer

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

[Diagram showing the components and operation of the Achromatic Nulling Interferometer]

- Pupil Input
- Bright output
- Null output
- Dispersive Components
- Symmetric Beam Splitters
- Variable shear, s
- For Achromatic Null
- Variable delay

[Graph showing null contrast vs. wavelength (μm)]
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
Post Starlight suppression wavefront sensing

- $\theta^4$ nuller
- Shot noise, Detector noise, pixelization included
- Contrast improvement $\propto$ integration time$^{-1/3}$

- Reference: Shao et. al.
Session XIV
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
Progress in Demonstrating Deep Nulling

Laser Null: $7 \times 10^{-7}$

White Light Null: $7 \times 10^{-7}$

Reference: Schmidtlin et. al.
Session XII
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:**
  - 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 $126.2\mu m$
  - $NA=0.048 \ @ \ \lambda=0.632\mu m$

See SPIE 5170-22, Liu et. al
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
Boston University MEMS Pathfinder Deformable Mirror

- 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
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