EPIC

Goddard Space Flight Center

Extra-Solar Planetary Imaging Coronagraph

Rick Lyon

TPF Workshop 09/28-29/06

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EPIC Team

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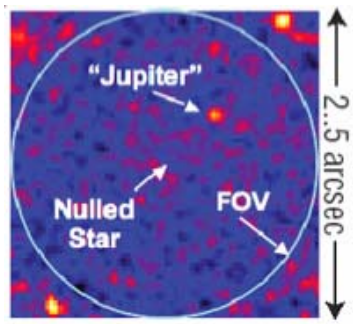
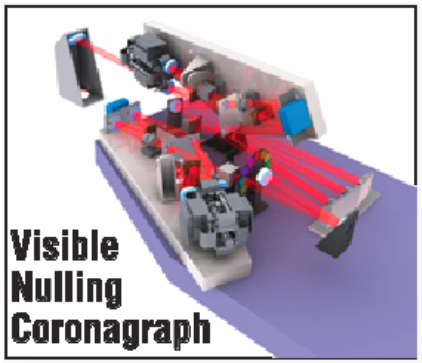


Post-processed (matched filter)

Epic: "*long series of events characterized by struggle*"

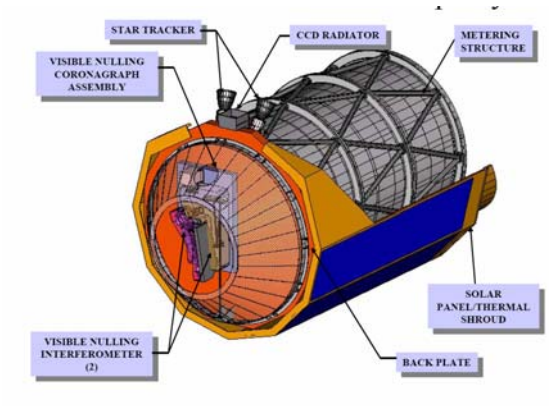
Epicurus (342 - 270 B.C.) 'universe must be infinite and contain an infinity of worlds.'

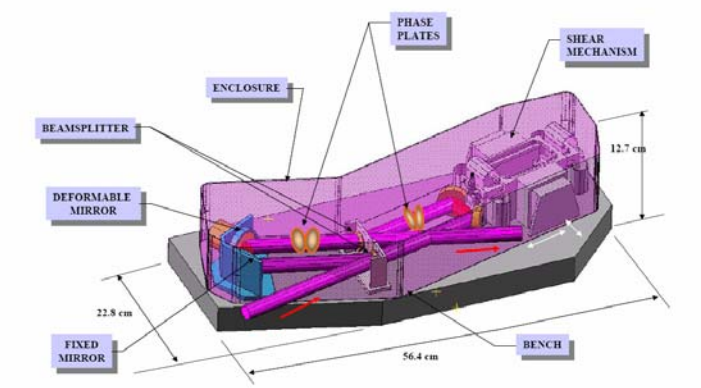
EPIC - *Extra-Solar Planetary Imaging Coronagraph*



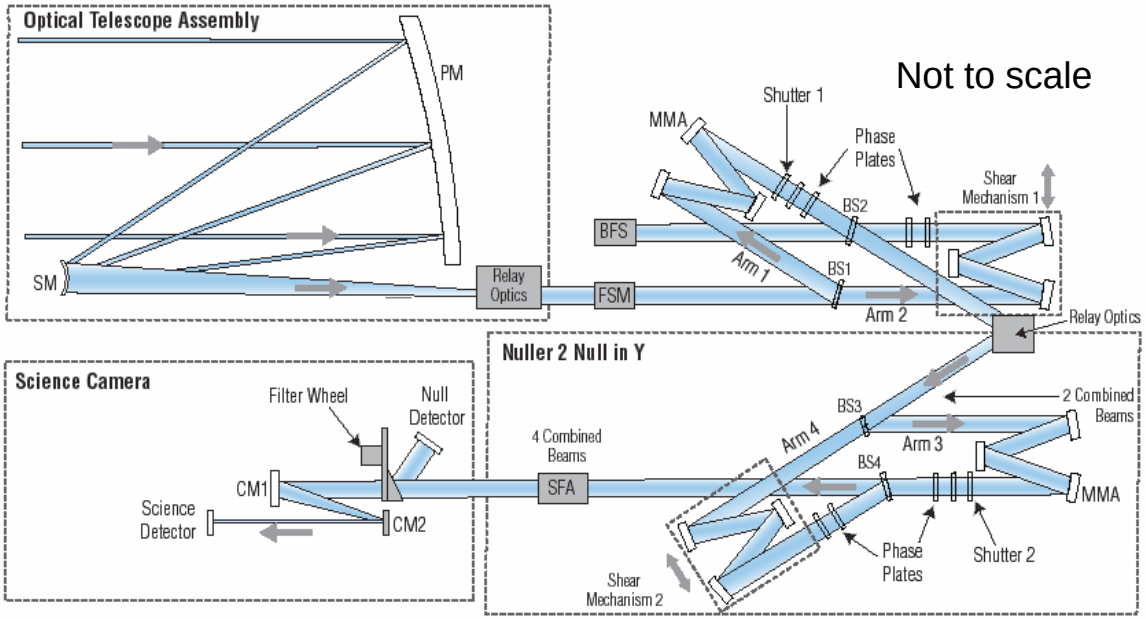
Overview

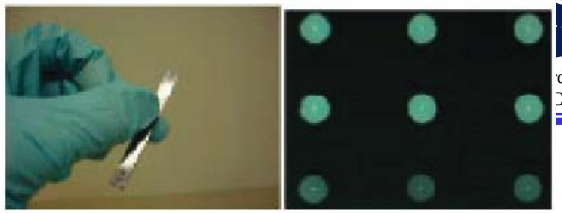
- **Science**
  - Jovian planets ~1 - 100 J masses
  - Proposed under FY06 NASA/Discovery (pending)
  - PI: M. Clampin - Involves GSFC/SAO/JPL/LMCO/BALL
  - Detect & Characterize Jovian planets
  - IWA ~ 186 mas (~2.7 λ/D @ λ = 500 nm)
  - Null => 10^{-6}, Contrast < 10^{-9} (15% bandpass)
  - Throughput ~ 12-15% (varies with shear)
- **Mission Concept**
  - Mission Life: 3 yrs, 5 yr goal
  - Orbit: Heliocentric Earth Trailing
  - Spacecraft: BATC-Kepler
  - Instrument: LMCO
  - S/C Pointing: 1 arcsec 3σ/axis
  - Pointing: 15 mas 3σ/axis
- **Instrument**
  - OTA: 1.5 m off-axis unobscured
  - High Contrast Imager: Visible Nulling Coronagraph
  - Wavelength 450 - 850 nm
  - OTA Wavefront Error: ~λ/20 rms, ~ $1/f^3$
  - Active Null Control (~1/1000 sec) via 2 DM's and SFA



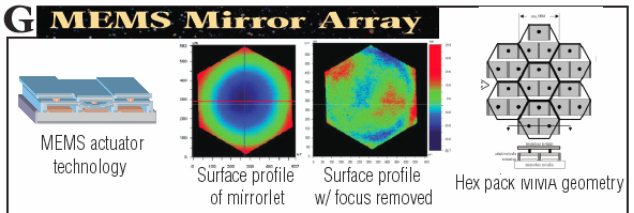


EPIC Technologies



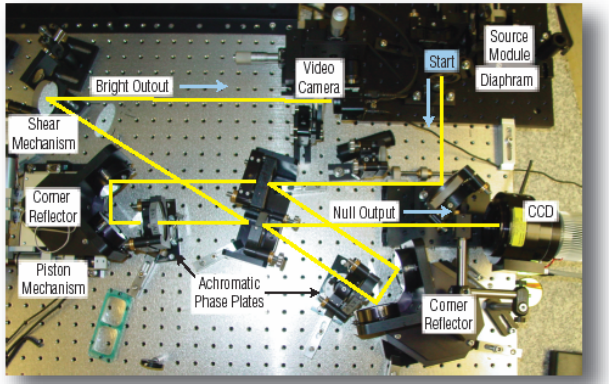


EPIC's spatial filter array consists of a compact fiber bundle (left) composed of light isolated fibers (right) sandwiched between two lenslet arrays. Col J. Ge has fabricated spatial filter arrays exceeding EPIC's required tolerances.



EPIC's nullers employ commercially available MEMS mirror array technology. EPIC's MMA's are required to provide piston/tip/tilt control. Boston Micromachine (BMC) markets MEMS mirrorlets that meet or exceed our requirements for stability, range and resolution. UC Santa Cruz, with BMC, has demonstrated the required stability over periods longer than EPIC requires. GSFC has an SBIR with BMC for flight qualification of MMAs and BU/NASA/JPL have funded BMC to provide the MMA for the PICTURE flight mission.

EPIC's instrument concept has been implemented using the visible nulling coronagraph testbed at NASA/GSFC (shown below). White light nulling has been achieved through spectrally tunable achromatic glass plates resulting in a broadband null. Efforts are under way to implement direct null control with a BMC MMA and a SFA.



Technologies:

- 1.5 OTA (λ/20 rms)
- 1 - Fine steering mirror
- 2 - Matched sets of BS
- 2 - Discrete DMs (~1200 mirrorlets)
- 4 - pair Achromatic phase plates (glass/grating)
- 2 - Precision/Stable mechanisms
- 1 - Spatial Filter Array (SFA) (~1200 fibers/lenslets)
- 1 - Photon counting detector
- Null control (~1/1000 sec)

Risk associated with technologies acting in concert

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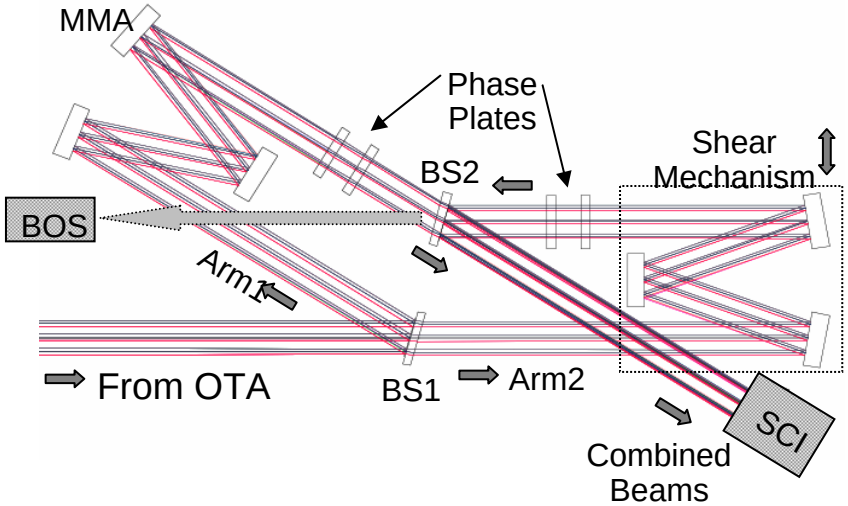
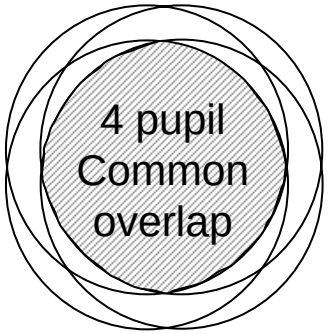
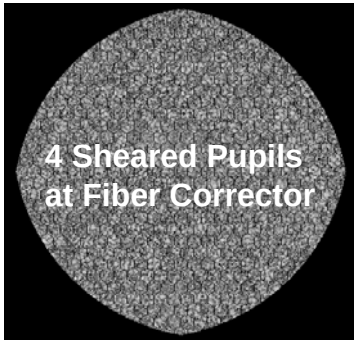
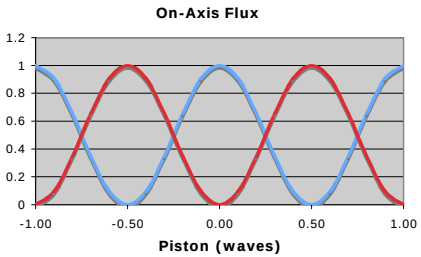


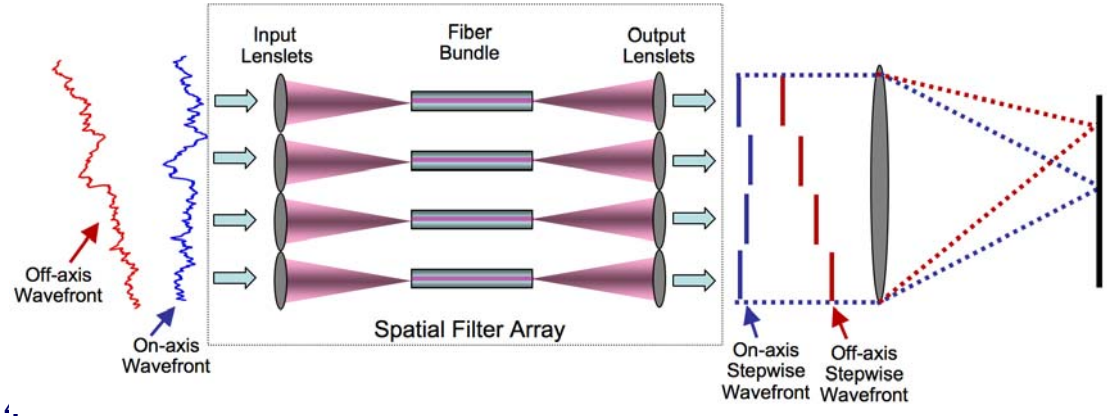


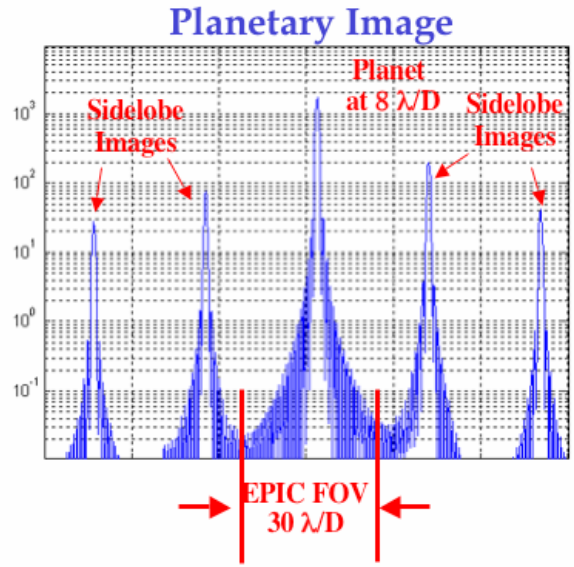




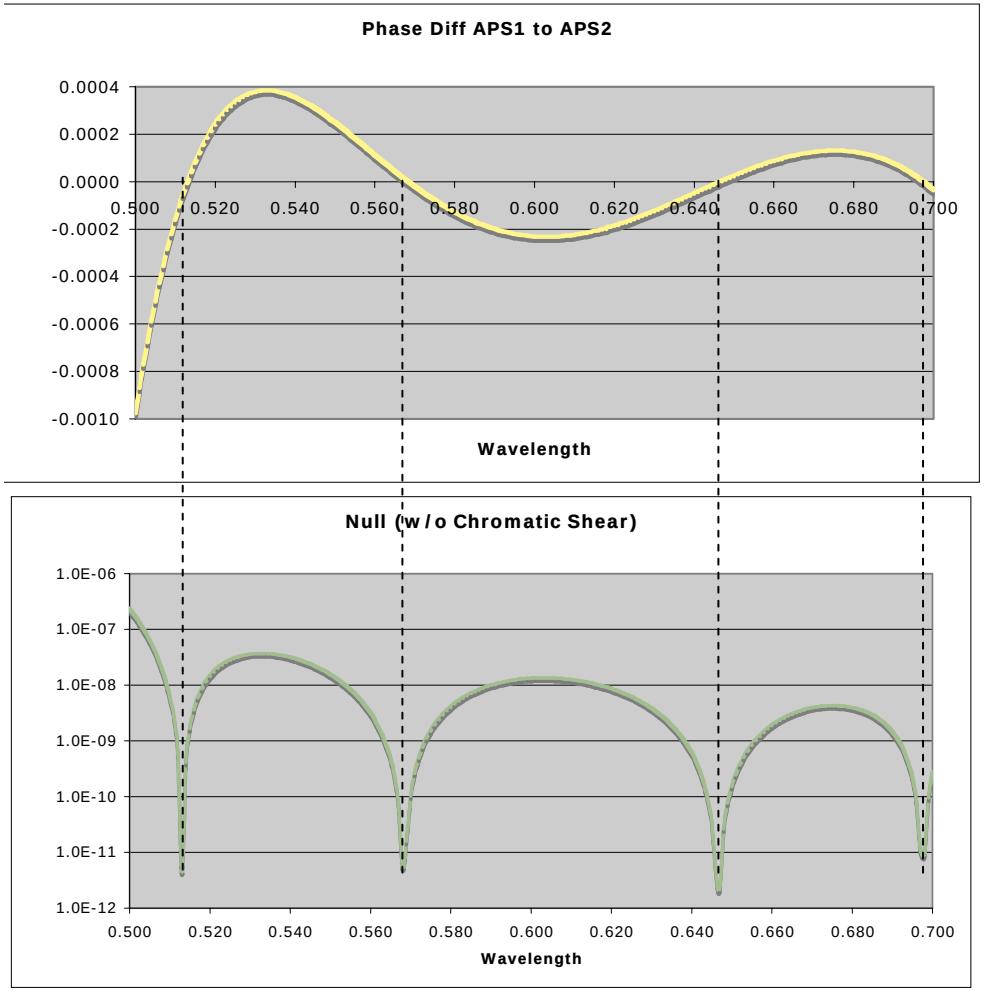
Sky Transmission Pattern

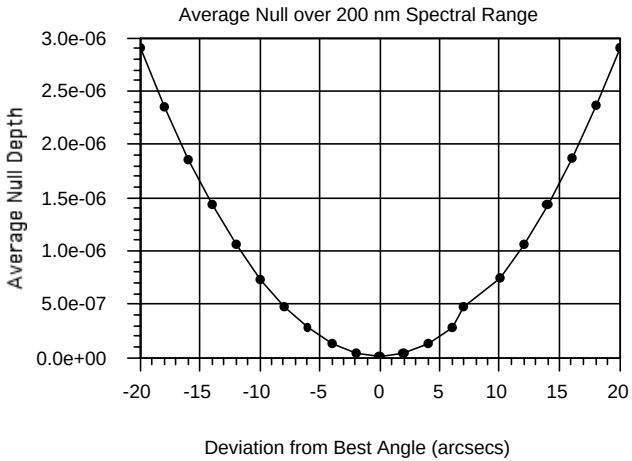
X/Y Nuller: $T(\theta_x,\theta_y) = \sin^2\left(2\pi s_x \frac{D}{\lambda}\theta_x\right)\sin^2\left(2\pi s_y \frac{D}{\lambda}\theta_y\right)$





Achromatic Nulling





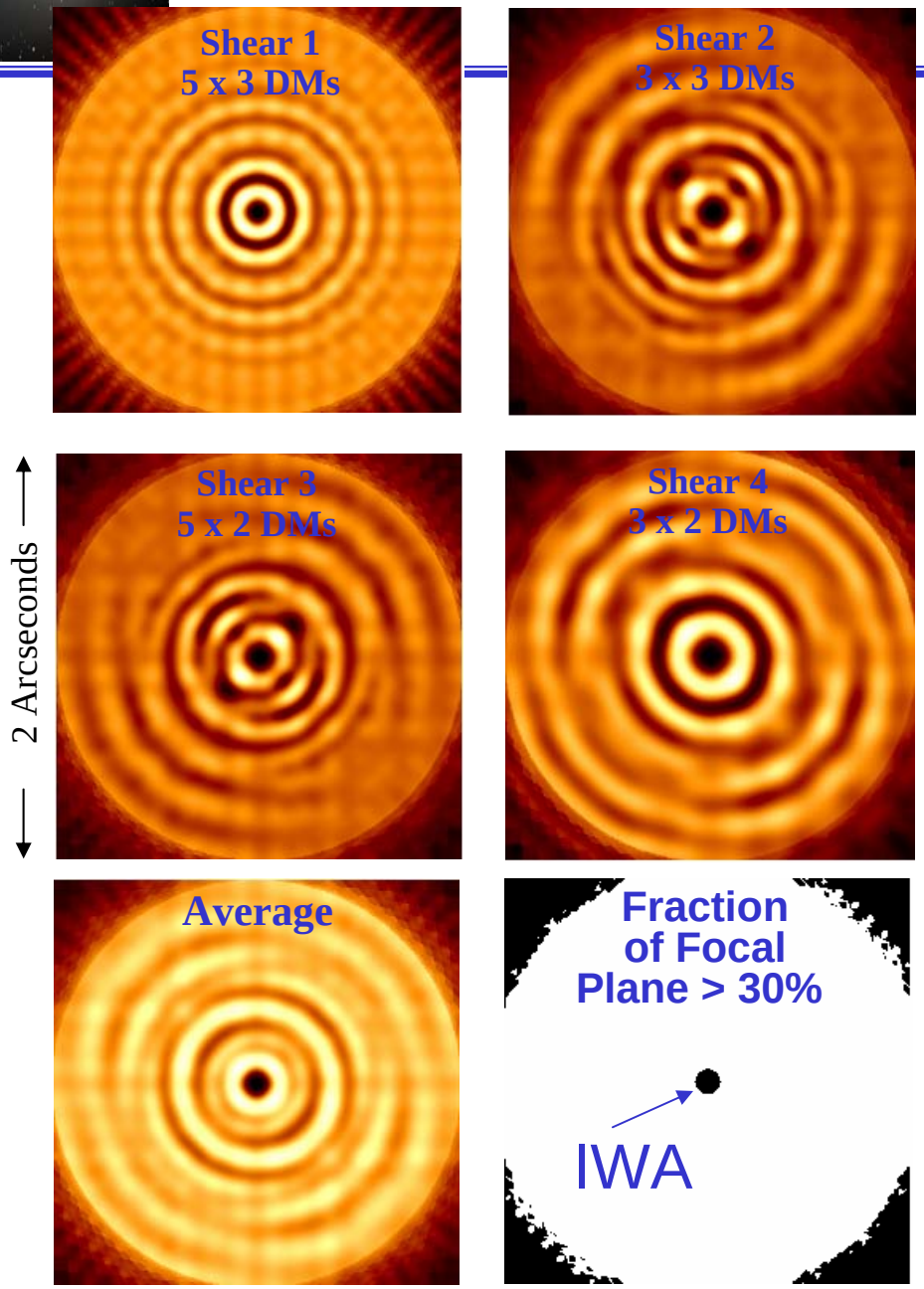
Theoretically:

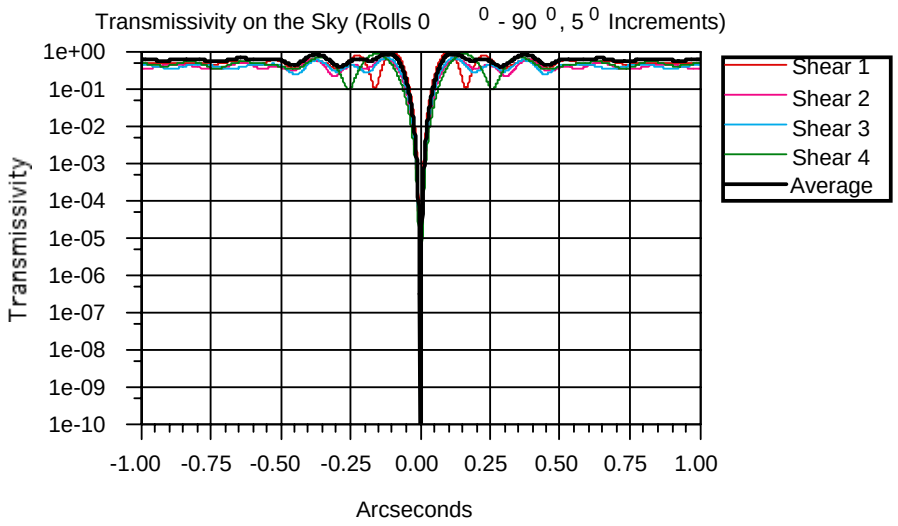
- 4 plates (2 per arm per nuller FS, BK7)
- Dispersion => path length deviation per λ
- Function of thickness, angle, $n(\lambda)$
- Solve via using simulated annealing
- 4 zero crossings => 4 deep nulls
- Null depth < 10^{-7} over range e.g. 0.5 - 0.7
- Sensitivity: σ ~ +/- 2 arcsec/glass
- Can be done with gratings / grism also…

Practically:

- Recently achieved Null with 2 plates
- More difficult w/ 4 plates
  - Allignment approach, actuated each plate
  - set plate normal with autocollimnator
  - angularly tune
- Plates must be retuned in orbit

Shear / Roll Optimization

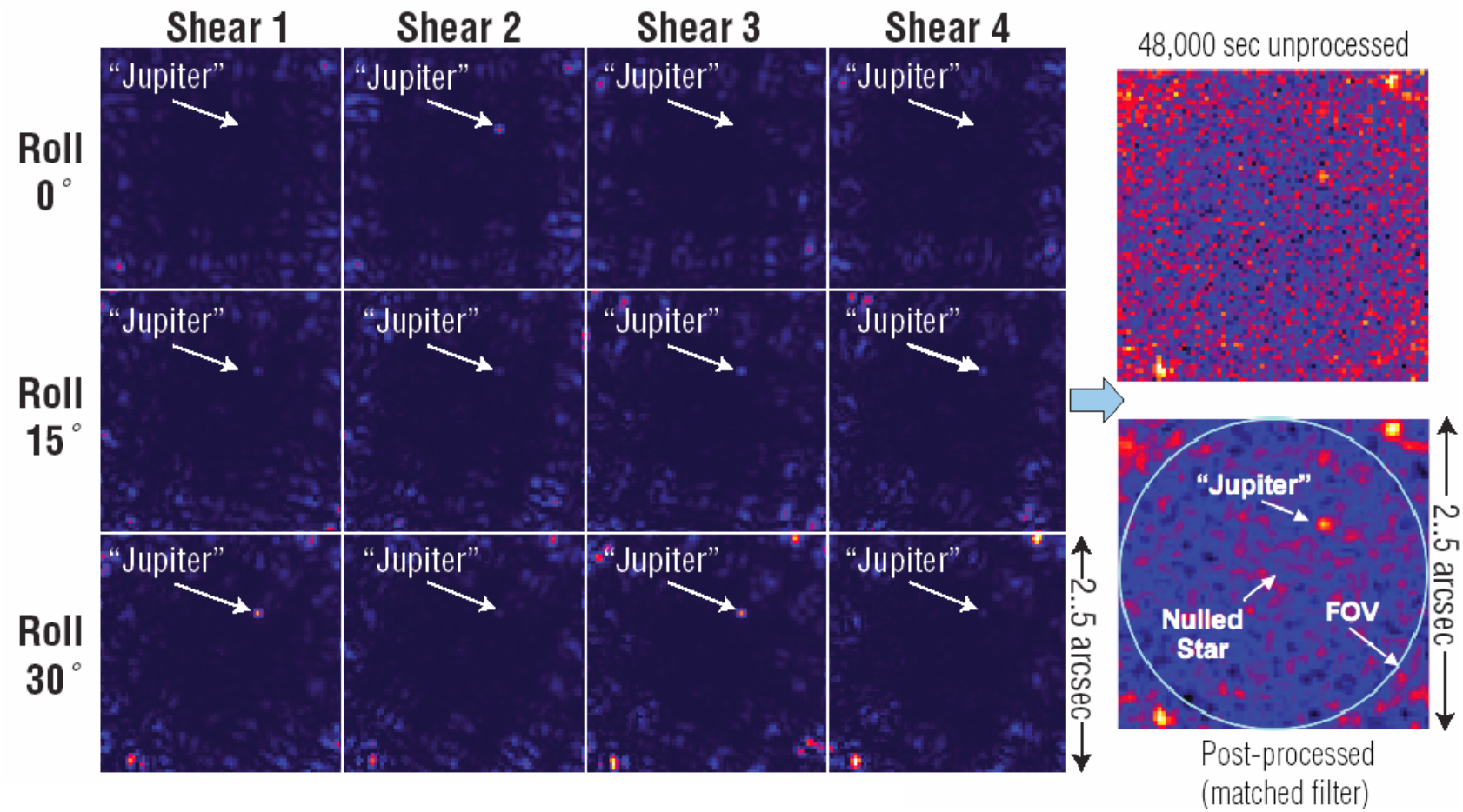




- Sims: 4 shears & roll in 5^0 increments to 90^0
- Minimize EPIC operational overhead
  - Discovery mode minimal ~4 shears/3 rolls
  - Characterization ~ 1 shear at 1 position
- Optimal pattern still being looked at

EPIC *Discovery* Mode

- While searching for planet (Discovery mode)
- 12 separate (3 rolls/4 shears) 4,000 sec exposures
- Null Control every 1,000 secs
- 560 +/- 42 nm filter



EPIC Visible Nulling Coronagraph Testbed

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3 Main Assemblies:

(1) Telescope Emulator (ASML optics)

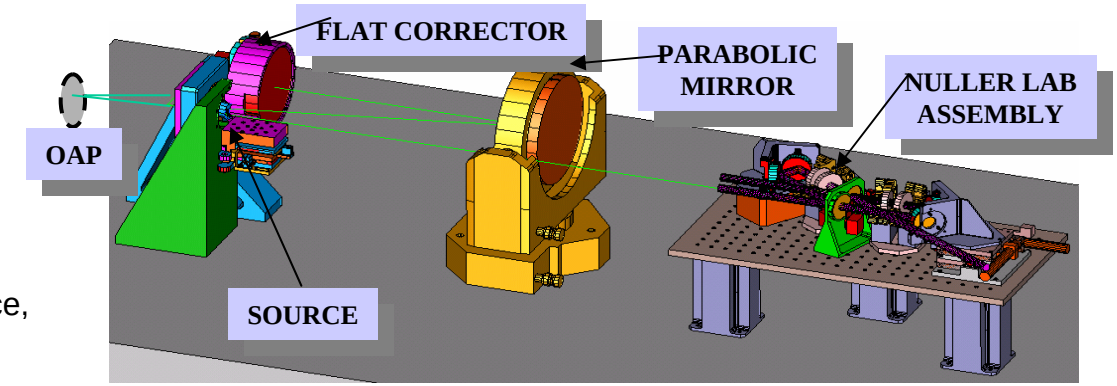
Control WFE from $\lambda/424$ to $\lambda/20$ rms
Fiber source, pellicle BS, OAP, Flat…

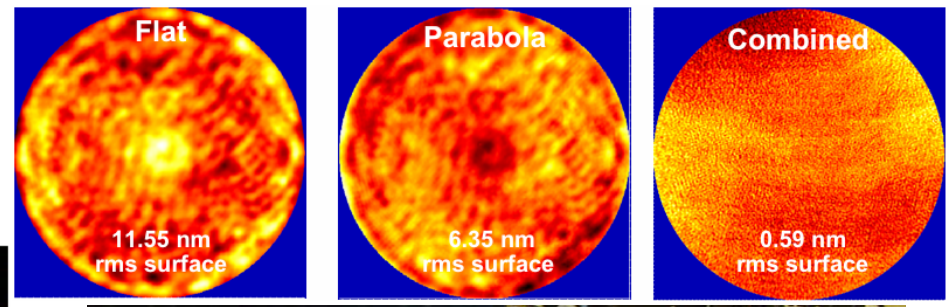
(2) Visible Nulling Coronagraph (LMCO)

2 BS, 4 achromatic plates, actuators,
HeNe, Diode Laser, White light fiber source,
HOE, CCD, theodolites, CMM, Davidson

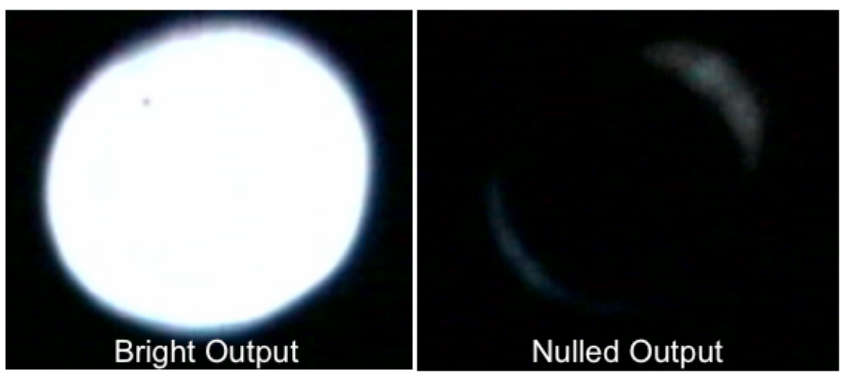
(3) Fiber bundle test fixture

BS, Fiber Bundle, Deformable Mirror, CCD

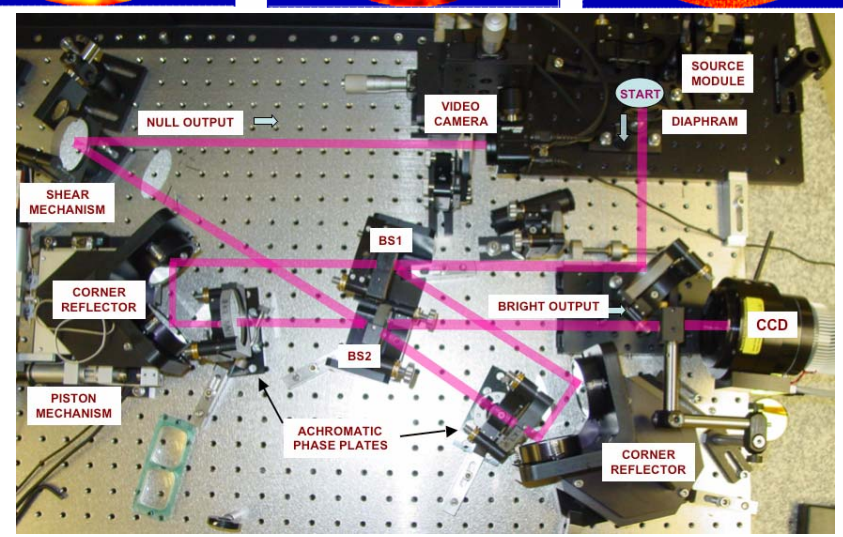




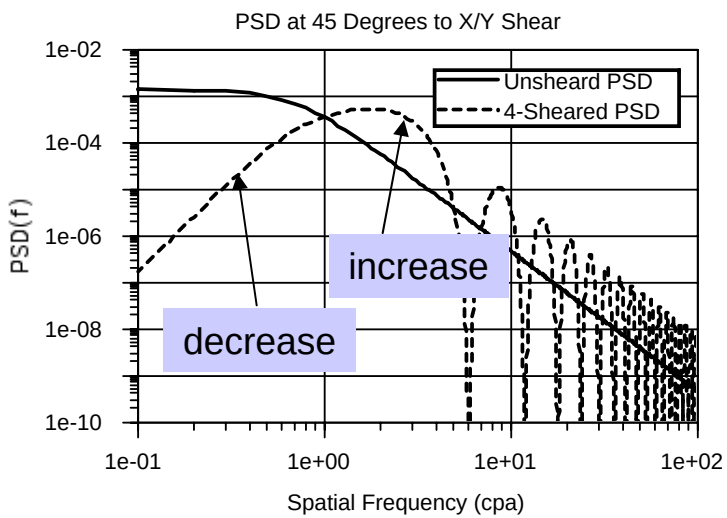
- Custom vacuum tank on-order
- Moving to GSFC's AIM facility
- Supercontinuum source

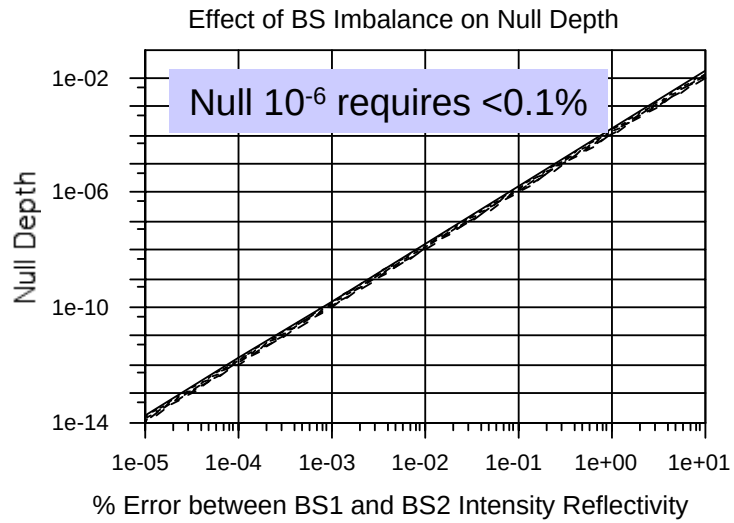


$\Delta\lambda$ ~ 500 - 560 nm
Observed null to ~10^{-3}
Theorectical contrast ~10^{-6}
Currently stability limited

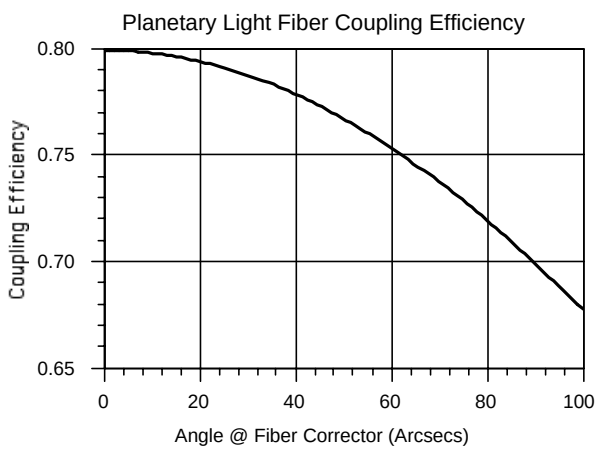


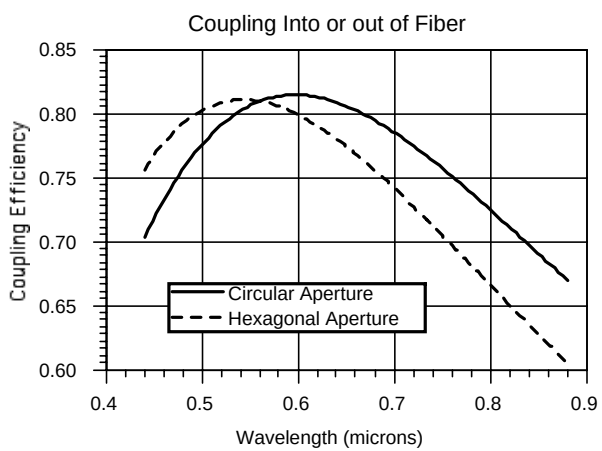
Some VNC Sensitivities

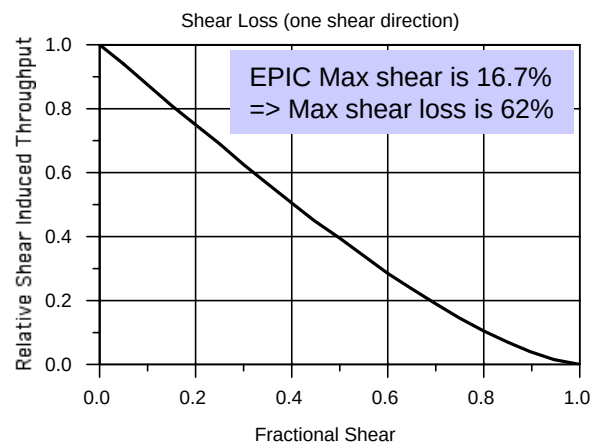




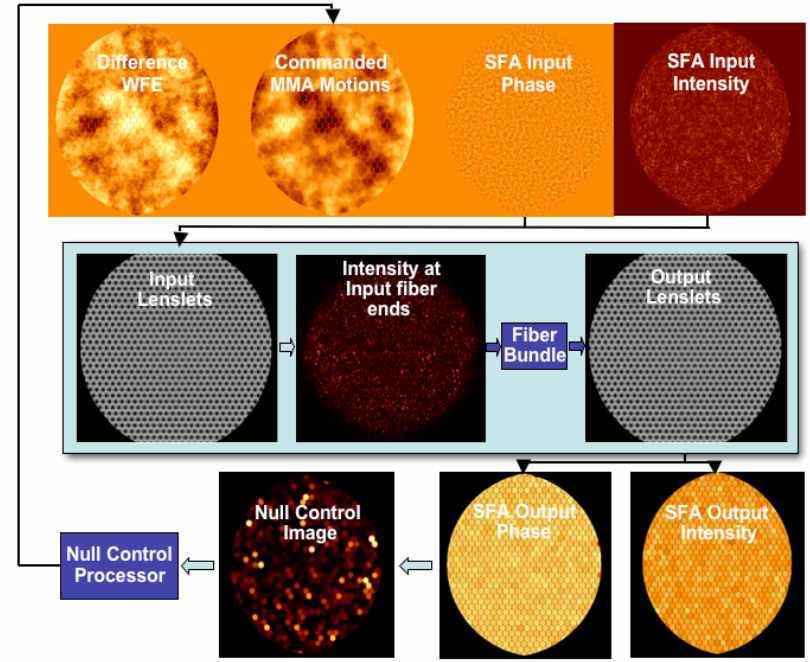
Open Loop: Shear decreases low cpa sensitivity
Increases mid cpa freq sensitivity
Closed Loop: segmented DM w/SFA corrects to N/2 cpa
Drift/null control step: sets requirements

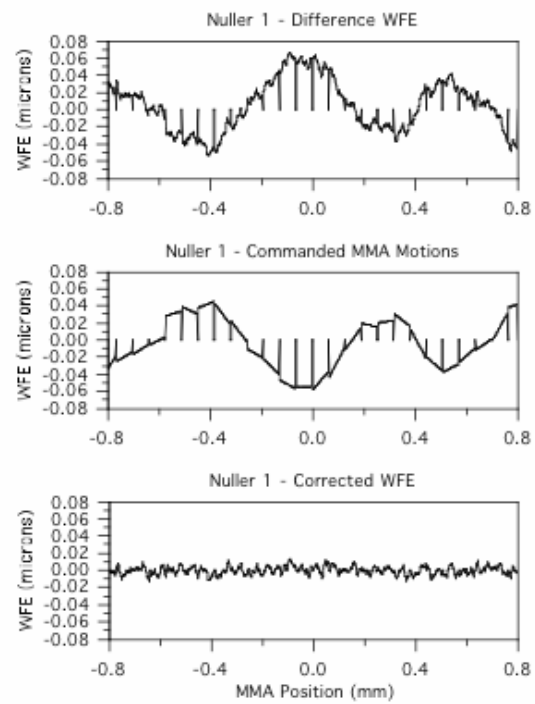






Null Control





- SFA pupil image to photon counting detector
- Multiplex null control (implicit WF & Amp)
- Each sub-Ap independently (~1200 subAps)
- Assume full bright flux:
  - V=5, A = 1.77 m^2, λ = 500 - 575 nm, T = 12%
  - Rate ~ 13275 photons/sec/subaperture
- Reduce null from 1.0 to <10^{-7} with gain/step ~0.1

$$N_f = Null \cdot N_0 = g^{nStep} N_0 \Rightarrow nStep = 7$$

- such that final SNR = 5

$$\sqrt{N_f} = \sqrt{g^{nStep} N_0} = SNR_f \qquad N_0 = R\Delta t_{step}$$

$$\Delta t_{Total} = \frac{nStep \cdot SNR_f^2}{g^{nStep} R} = \boxed{131826 \text{ sec (37 hrs)}}$$

Initial null control
Worst case:

Closed Loop:
- drift from 10^{-7} to 10^{-6} null
- bring back down to 10^{-7}
- retune for each shear/roll
- retune for each filter

$$\Delta t_{step} = \frac{SNR_f^2}{g^1 R} = 0.019 \text{ sec}$$

EPIC Null Control Experiment

Simple Michelson Interferometer

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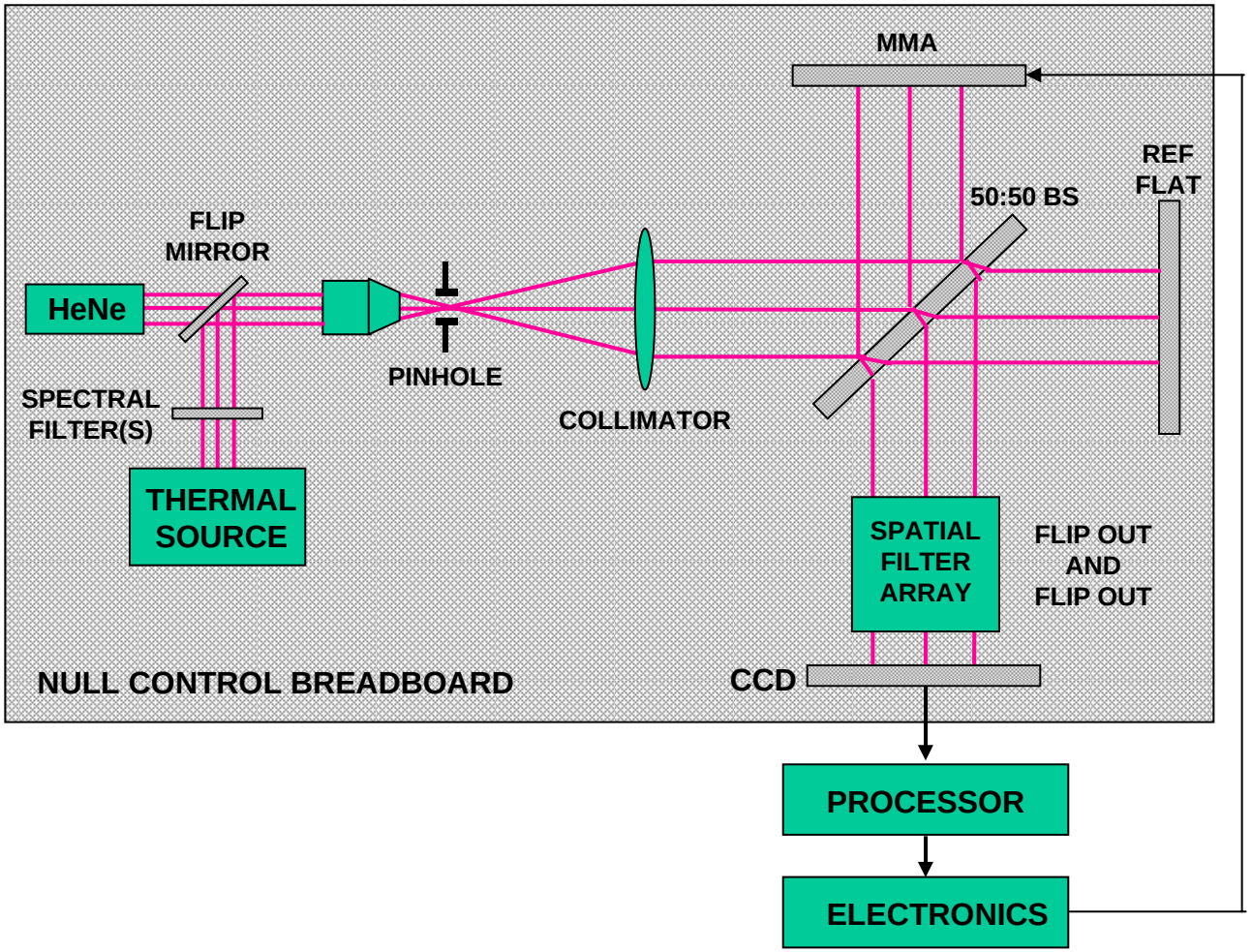
Null Control Breadboard

- Bias reference flat reflectivity to be less than SM reflectivity.
- Entire breadboard is small 6” x 12”
- Thick stable breadboard > 4”
- Working height < 5 cm
- Totally enclosed (air/straylight)
- Experiments:
  (1) SM piston/tip/tilt beam sub-aps w/ HeNe and w/o SFA to demo null depth control to $<10^{-6}$
- DM piston/tip/tilt beam sub-aps w/ filtered (15%) white light w/o SFA to demo null depth control $< 10^{-4}$
- DM piston/tip/tilt beam sub-aps w/ filtered (15%) white light w/ SFA to demo null depth control $< 10^{-7}$

Note:
Simple testbed allows for fine tuning of null control algorithms, calibration and performance assessment of MMA and spatial filter array.



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Summary / Conclusions

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- EPIC VNC Approach viable for Jovian planets
  - IWA => 2.7 λ/D
- VNC approach viable for Terrestrial planets
- Null Control:
  - No intermediary WF/Amp sensed
  - Sense only that which is important => Null
  - Pupil plane sensing => parallel / multiplexed
- Throughput varies with shear (12 - 15%)
- OTA WFE + non-common path + stability errors drives DM
- OTA Amp nonuniformity driven by chromatic tilt leakage
- For Jovian planets component technologies meet requirements
  - issues are scalability of DM/SFA, demo of null control, system level demo
- Doesn't require beyond current state of the art (no tall poles)
- Doesn't suffer from 1 angstrom mask tolerance problem
  - no optics at or near focal planes
  - doesn't suffer from 25 λ/D limitation
- Testbeds enable model validation/correction, null control algorithms
- Modeling only gets you so far… need lab demo's