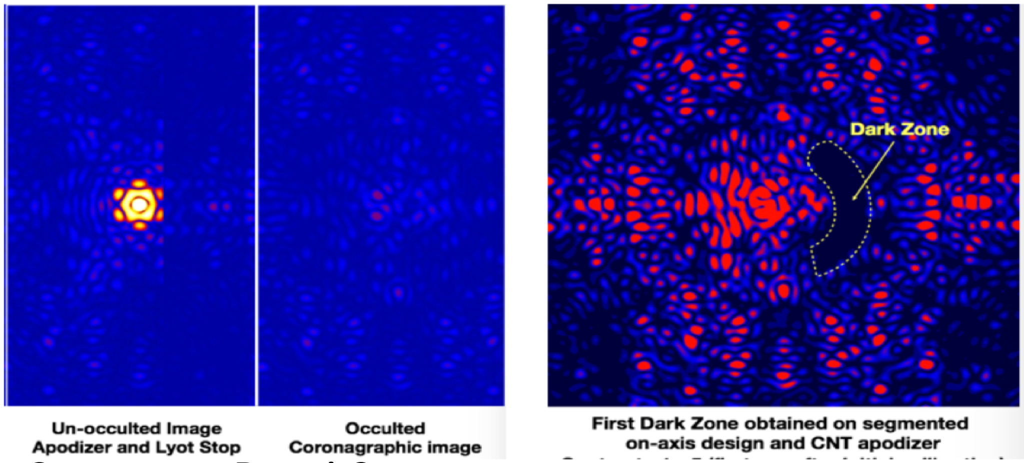


Courtesy; Remi Soummer

NASA SBIR: Proximity Glare Suppression Using Carbon Nanotubes

John Hagopian

November 6, 2018

SBIR Customers and Collaborators

- Phase I Customers
  - Remi Soummer – Space Telescope Science Institute HiCat Test Bed Lead Scientist
  - Ron Shiri NASA GSFC
- Phase II Customers
  - Eduardo Bendek – LUVOIR Ames NASA Test Bed
  - NASA GSFC – PACE/Ocean Color Radiometer Team
  - Ron Shiri/Jeff Livas - Laser Interferometer Space Antenna (LISA)
- Collaborators
  - Rich Corey – Front Range Photomask, LLC
  - Lance Oh – YNC Solutions
  - Peter Chen – Lightweight Telescopes

Why Carbon Nanotubes?

- ***Carbon nanotubes are the darkest material made by man***
  - Application of carbon nanotubes to instrument components can significantly improve the performance of scientific instruments
    - Enabling new science
    - Better observational efficiency
    - Simplification of stray light control
  - This SBIR focused fabrication on delivering components for evaluation in a coronagraphic test bed to investigate technologies for Exoplanet science
    - Shaped Lyot Stops
    - Reflective apodizer

Deliverable: Shaped Lyot Stops

- ***Lyot Stops occult on-axis light from a star at an intermediate focal plane***
  This allows coronagraphic instruments to view very dim planets orbiting the stars

Primary Technical Goals:

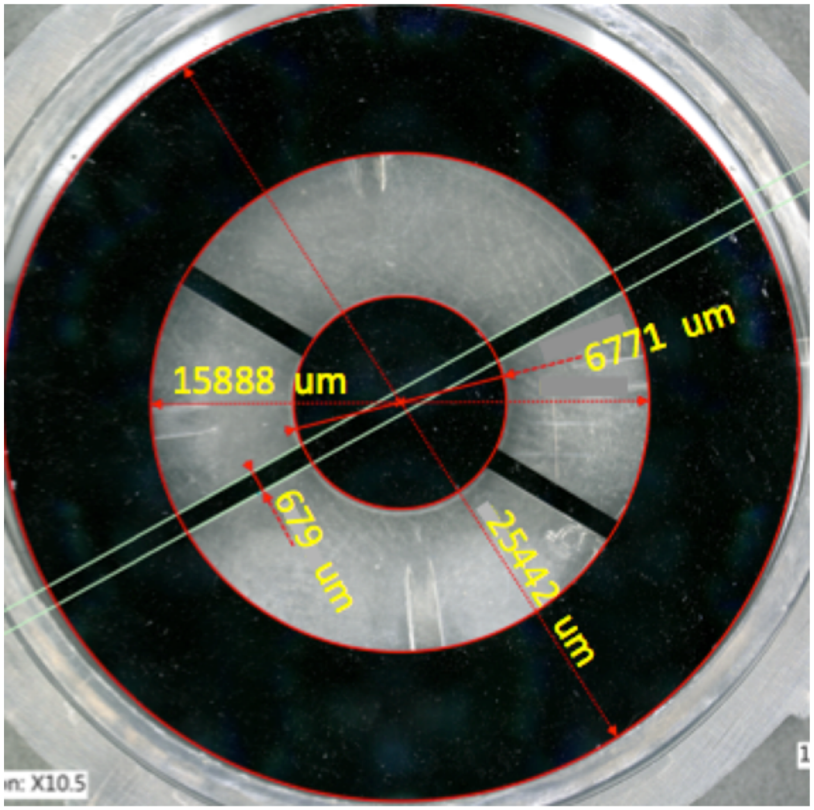
- ***Fabricate a sharp edged Lyot Stops using lithographic masks and wet etching*** to produce an optically flat and accurately dimensioned substrate
- ***Apply nanotube deposition to Lyot Stops*** – deposit short growth, dark nanotubes precisely

- For both deliverables:
- ***Robustness of adhesion*** to survive exposure to space flight qualification and the space environment; vibro-acoustic and thermal. However, the CNT coating and all other available CNT growths will remain a "no-touch" coating that will degrade with contact

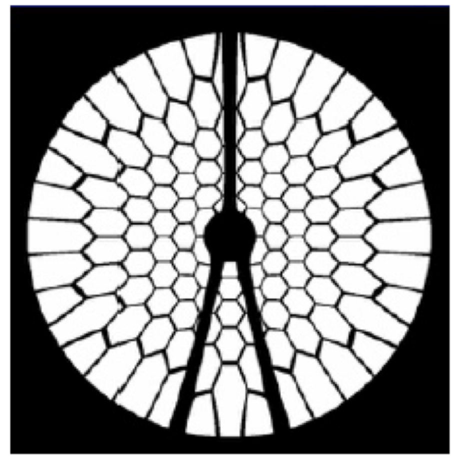
Shaped Lyot Stops

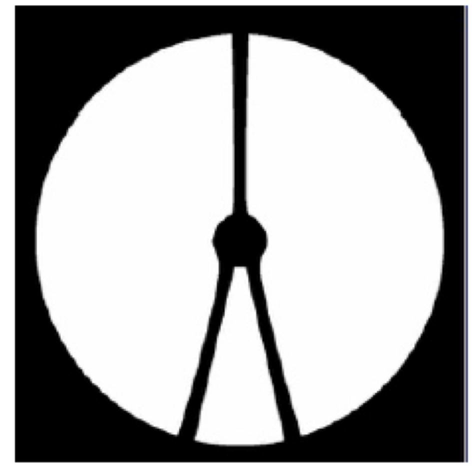
- ***Design and fabrication –***
  - *Worked with Remi Soummer from Space Telescope Science Institute to design a Lyot Stop for use in the HiCat test bed*
  - *Converted design to GDS file to create an e-beam written lithographic mask for precise patterning of mask in silicon*
  - *Patterned and etched Lyot stops from 300 micron thick silicon wafers*
  - *Controlled etch process to create a 57 degree edge angle for a sharp edged stop with precise dimensional accuracy*
  - *Developed short growth catalyst and applied it to both sides of Lyot Stops*
  - *Successfully grew nanotubes on both sides of Lyot Stops*
  - *Phase II Goal is to fabricate complex shaped Lyot Stops for LUVOIR Test bed at NASA Ames (Eduardo Bendek)*

Shaped Lyot Stops



Phase I Lyot Stop for HiCat Test Bed
Patterned to couple micron precision





Phase II Complex Lyot Stop Design for Luvoir Test Bed With and without Segments

Deliverable: Reflective Apodizer

- ***A patterned reflective apodizer*** resides in the pupil plane of a coronagraph and absorbs diffracted light from the structures in a telescope; the secondary mirror baffle, struts and segment edges. This creates a “Dark Hole” at some field positions where we may view the extremely dim companion planets

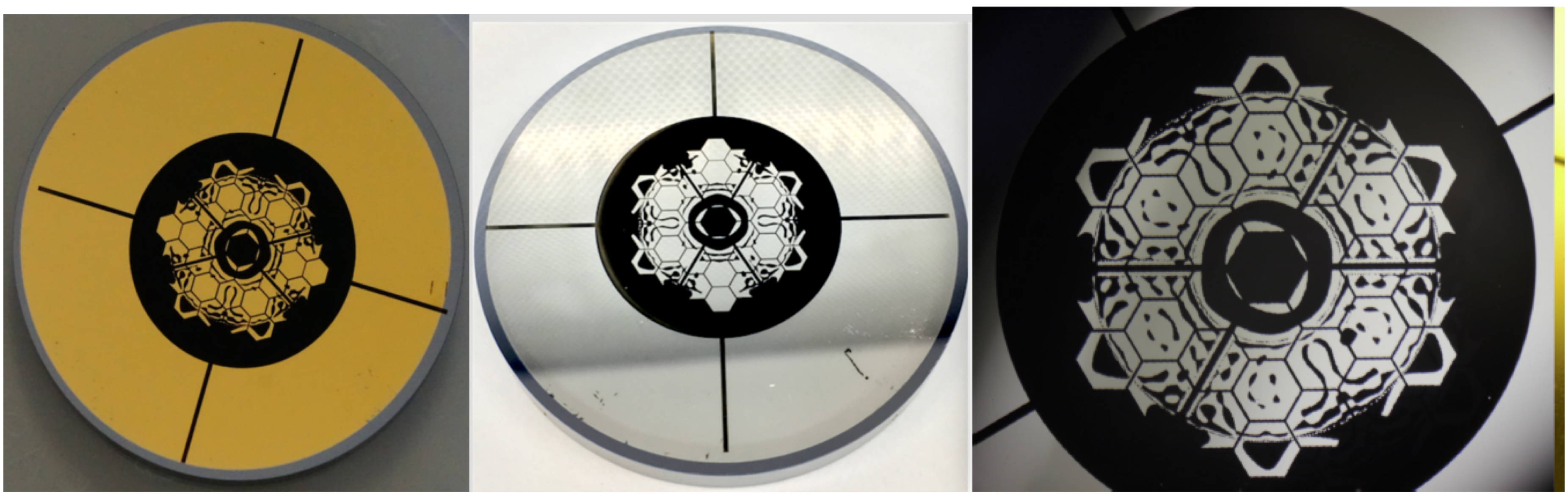
Primary Technical Goals:

- ***Excellent apodizer mirror surface figure –***

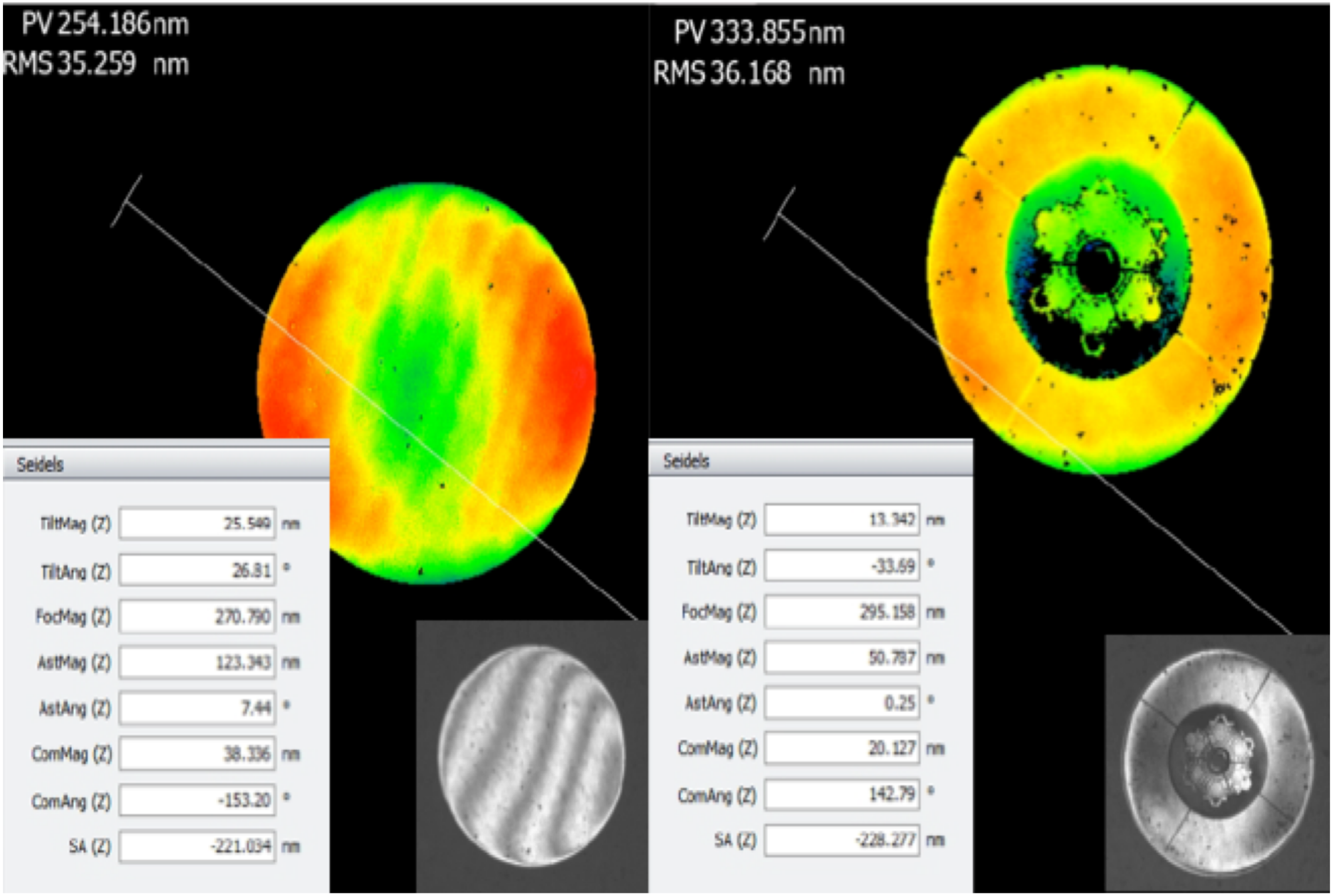
  Develop a mirror substrate and nanotube growth process compatible with the carbon nanotube growth that results in better than diffraction limited performance
- ***High apodizer reflectivity –*** develop a coating compatible with the carbon nanotube growth process (initially at 750 C)
- ***Patterned dark growth*** – pattern and grow nanotubes with features as small as few microns to support absorption of diffracted light

Phase I Apodizer

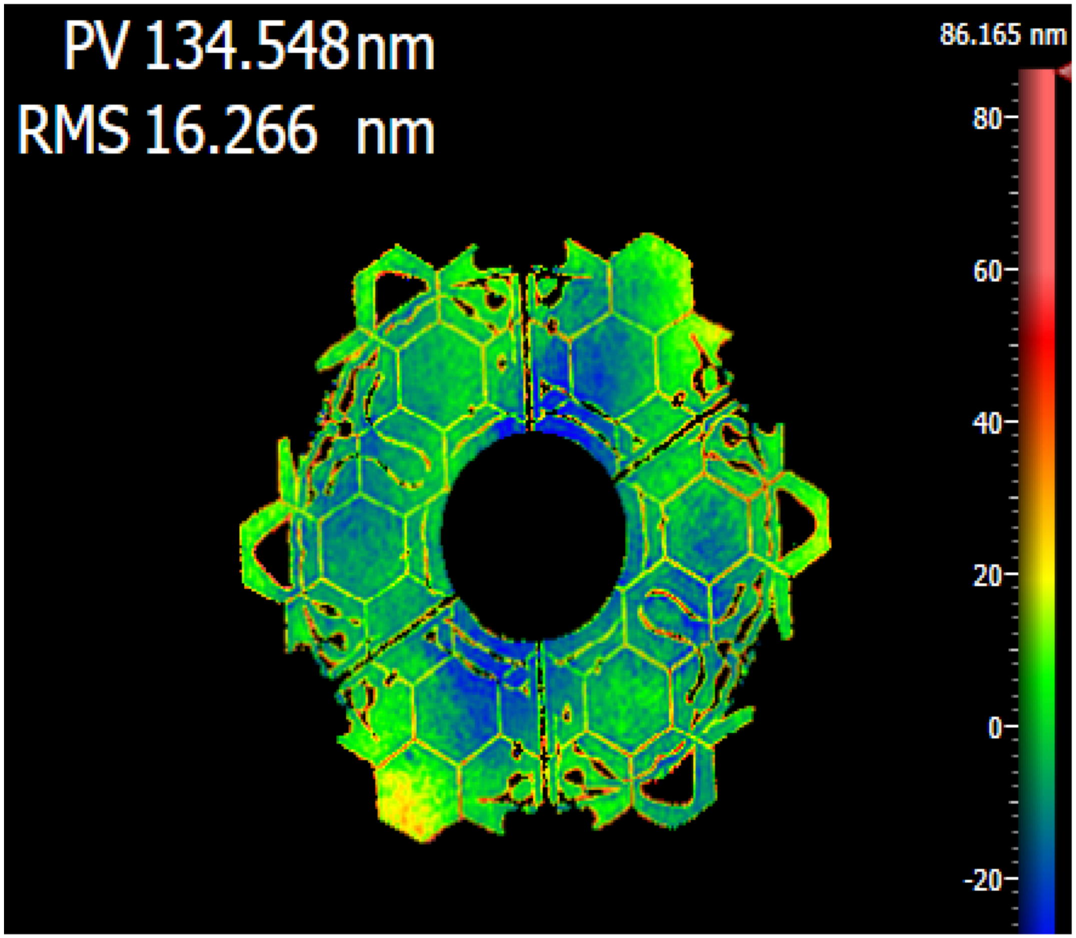
- Pattern designed by Remi Soummer et al. STScI
- Polished single crystal silicon substrate
- Demonstrated growth on gold and silver coating stacks



Mirror Surface Figure after Growth



Clear Aperture Surface Figure



Measurements at STScI indicates single digit nanometer wavefront error for delivered apodizer

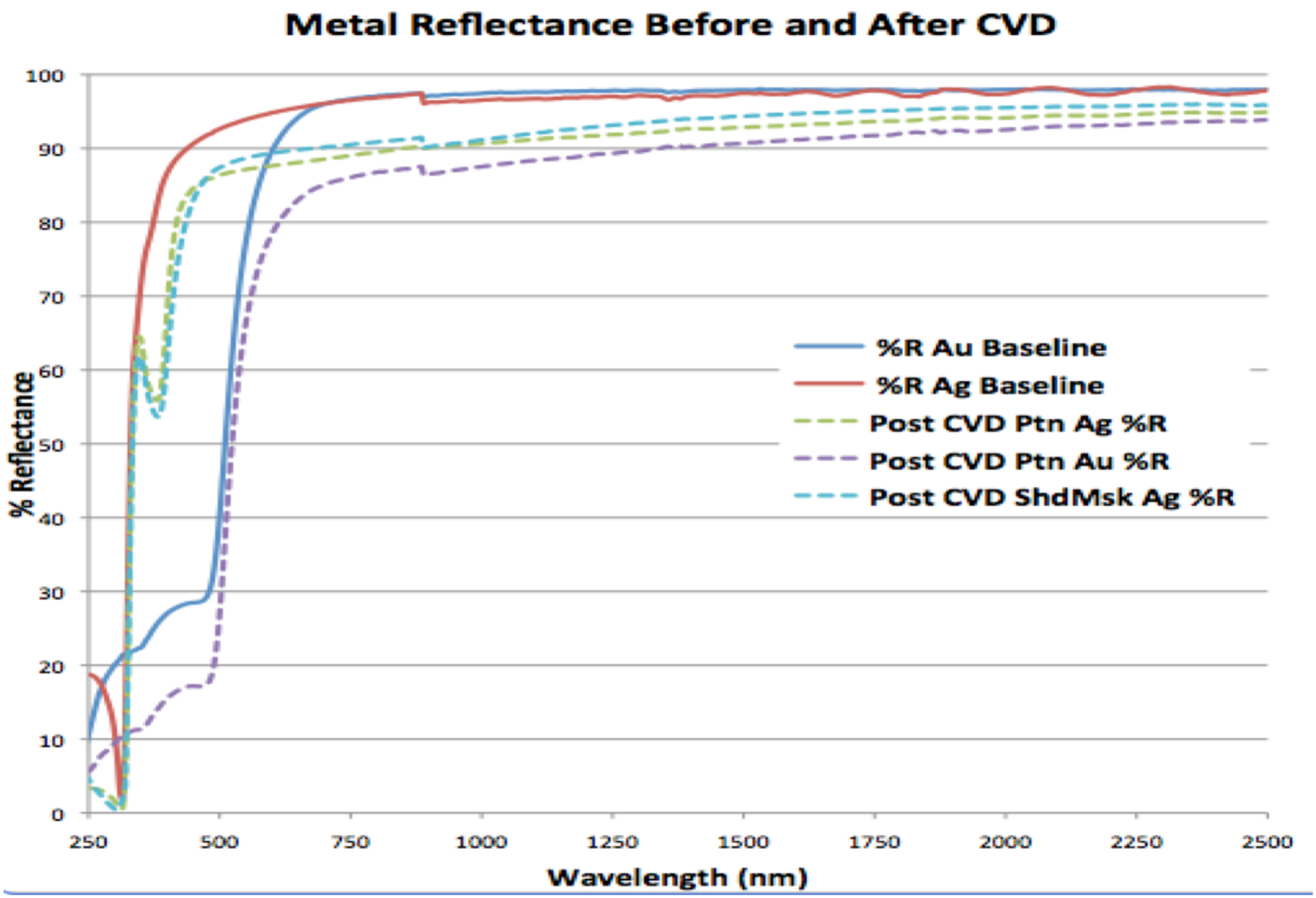
Growth Process Development

- Lower growth temperature and duration
  - "Flash Chemical Vapor Deposition (CVD)" process optimization limit duration to limit reflective layer degradation
  - Catalyst modifications to decrease growth temperature from 750 C to 650 C
  - Limited time in Phase I to optimized Plasma Enhanced CVD; work deferred to Phase II
    - University PEVD system restrictions
    - Delivery of dedicated PECVD occurred too late for effective optimization
  - Reflective stack optimization
    - Carbon nanotubes are not compatible with direct growth on gold or silver coatings so a coating stack was developed

Reflective Stack Performance Phase I

- Optimization resulted in good patterned growth on reflective stack
  - Two types of catalysts investigated
- Some degradation in reflectivity of gold and silver stack due to exposure to high temperature
- We are implementing modifications to our process to improve reflectance in phase II
  - Further optimization of flash CVD process
  - PECVD process for low temperature growth

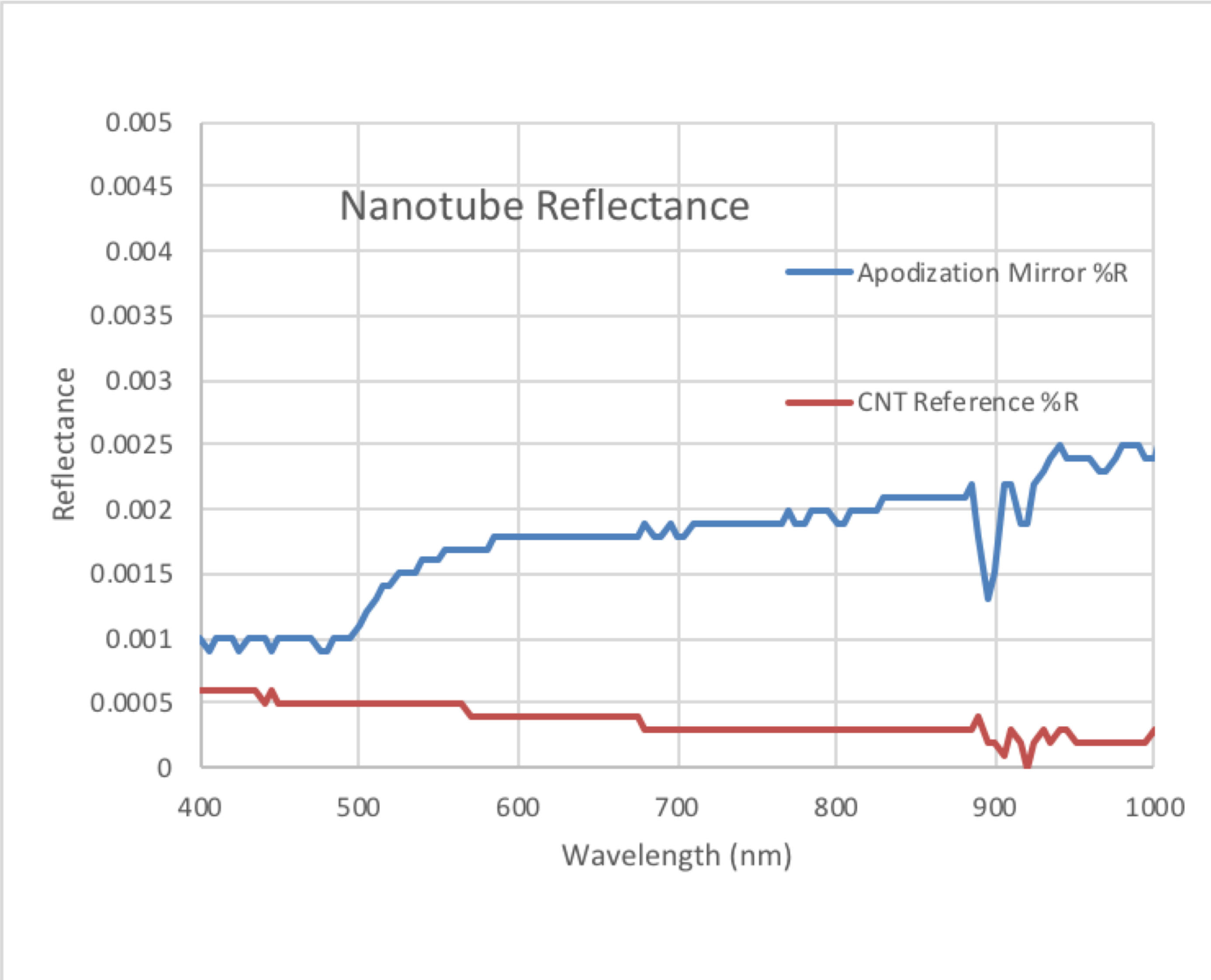
Coating Reflectivity



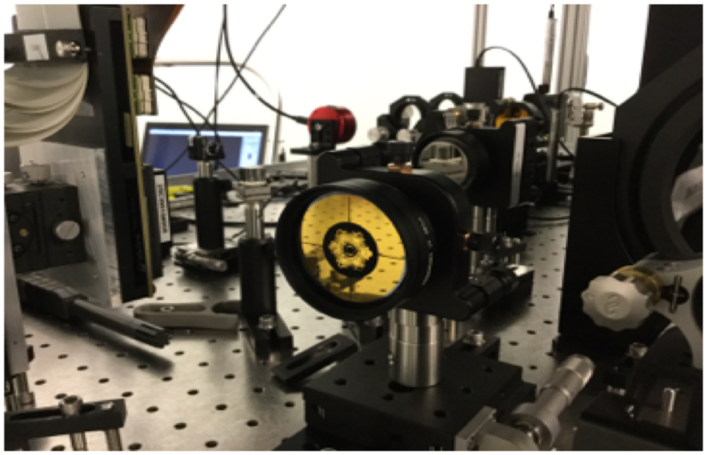
Nanotube Coating Performance

- Balanced approach in Phase I to achieve a deliverable apodizer
  - Catalyst selected for robustness to growth process and not maximum darkness
  - Plasma enhanced chemical vapor deposition development was delayed to Phase II to allow lower temperature to preserve reflective coating performance
  - Phase II will work towards darker growths compatible with reflective coating stack
    - Goal is an order of magnitude improvement in specular reflectance to match earlier growths on silicon

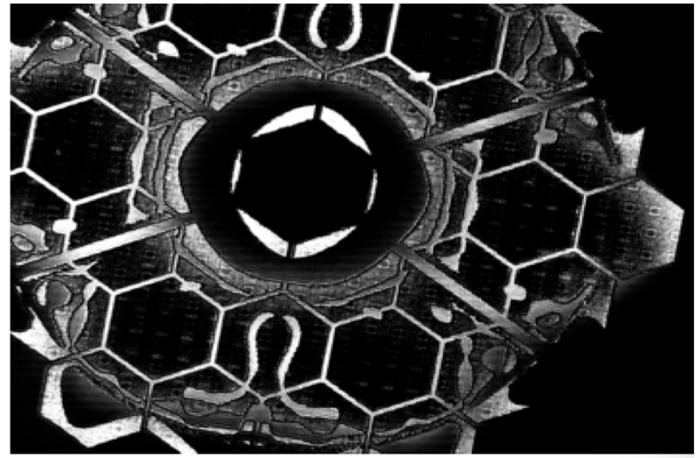
Phase I Nanotube Reflectance



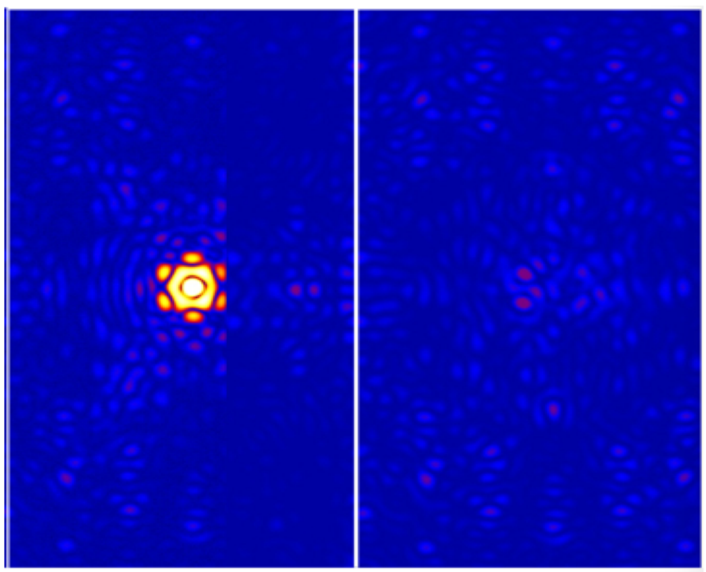
Performance of Deliverables in HiCat Test Bed



CNT apodizer installed in HiCAT

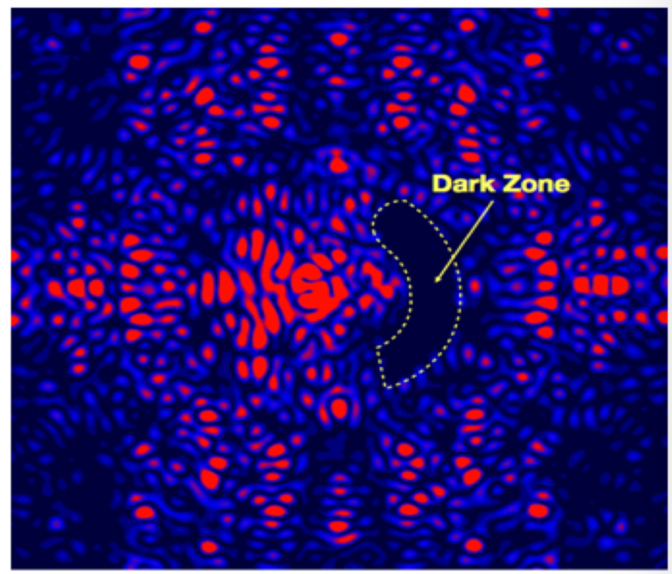


Coronagraphic image of apodizer pupil



Un-occulted Image
Apodizer and Lyot Stop

Occulted
Coronagraphic image



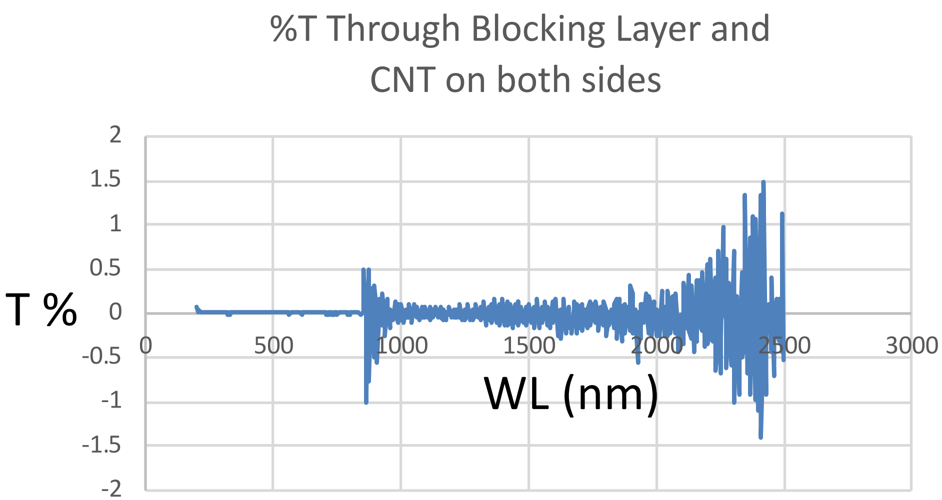
First Dark Zone obtained on segmented on-axis design and CNT apodizer
Contrast ~1e-5 (first run after initial calibration)

Dark zones using single-DM speckle nulling (1.7 x 10^{-6} monochromatic and 6.3 x 10^{-6} in 6% broadband) demonstrate this technology at TRL3.

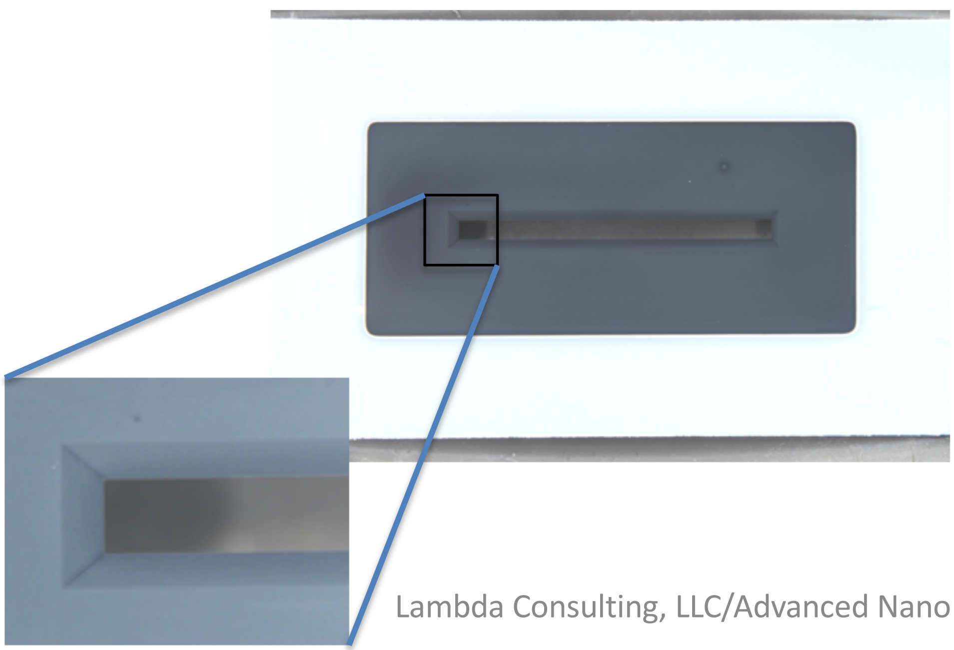
Field Stop for Ocean Color Instrument

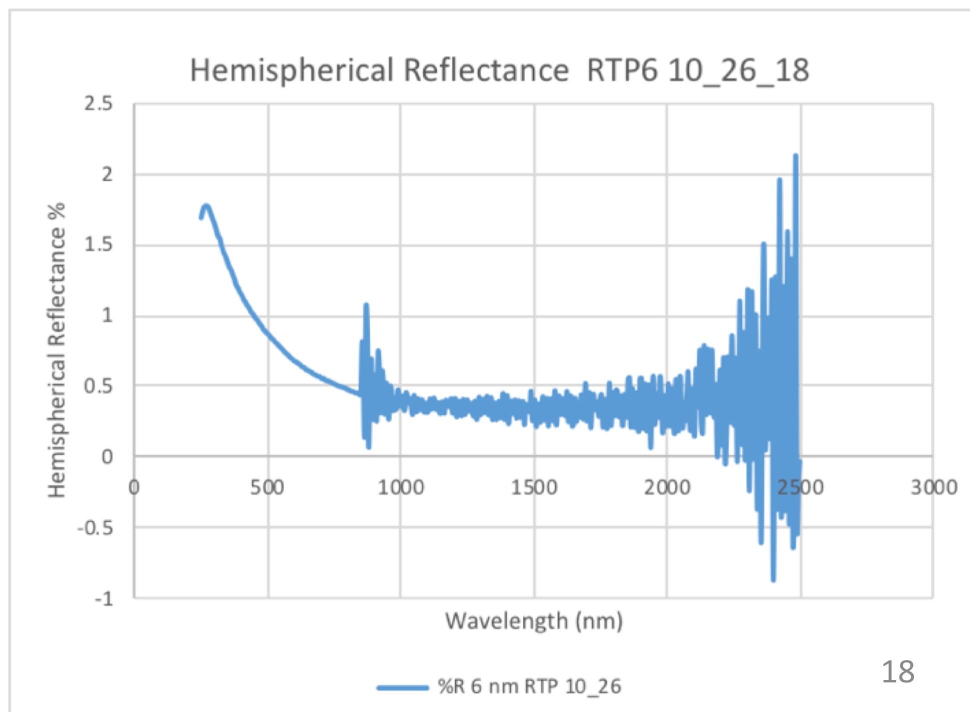
- New Phase II deliverable is an ETU component being evaluated for the flight OCI instrument on PACE
- Silicon substrate to allow precise etching with beveled sharp edge
- Controlled short growth nanotubes
- Nanotubes grown on blocking layer since silicon transmits past 1 micron wavelength
  - Developed blocking layer compatible with dark nanotube growth for short length nanotubes

Transmission of Blocking Layer and Reflectance of Nanotubes (preliminary results)



- 100% blocking while maintaining significantly better reflectance than alternate coatings
- Slit width is within microns of nominal 558 micron target
- Nanotube length is controlled and uniform at 5 microns even in beveled area





Phase II Goals

- Improved apodizers
  - Higher resolution patterning
  - Darker nanotube growth
  - Improved reflectivity of base layer stack
  - Grayscale apodizers
- Improved Lyot Stops
  - Darker short nanotube growth
  - Higher resolution features
- Improved nanotube filled paint for large area application
  - Greater than factor of four improvement on Z306
- Improved robustness
- Lower temperature growth
  - Plasma Enhanced CVD with activated catalysts
  - Flash CVD process below current 650 C growth temperature compatible with apodizer reflective stack