Visible Nulling Coronagraph

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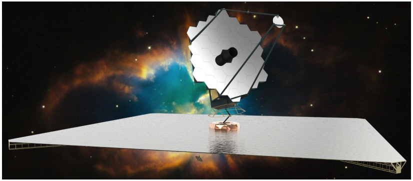
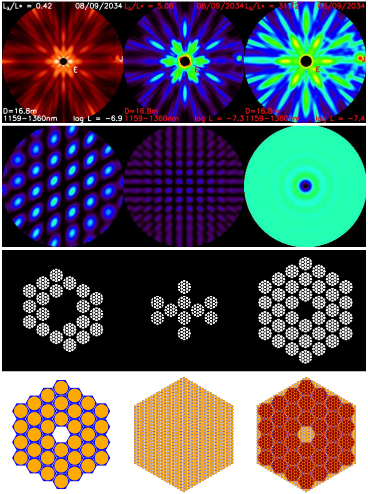
November 12, 2015

Science/Technical Objectives

1. Provide a coronagraph solution for exoplanet and debris disk discovery and characterization with a future large aperture space telescope
2. Optimize target yield by maximizing throughput
3. Achieve broadband ($> 10\%$) 10^9 raw contrasts at radial separations spanning $2.5 - 34\lambda/D$
4. Relax telescope stability requirements

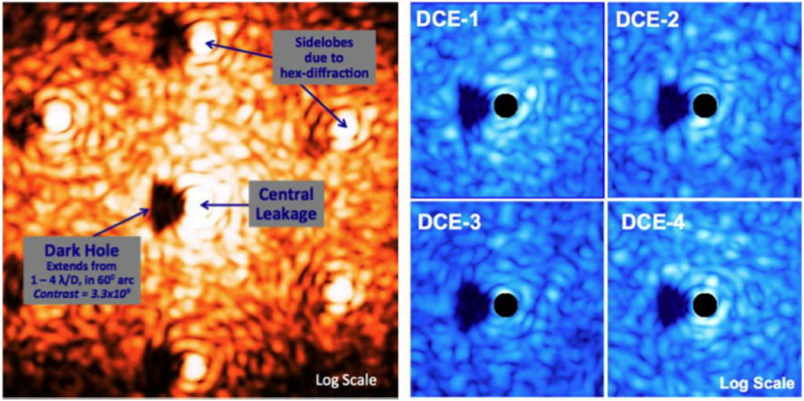


Hicks+, *Spirit of Lyot* (2015)



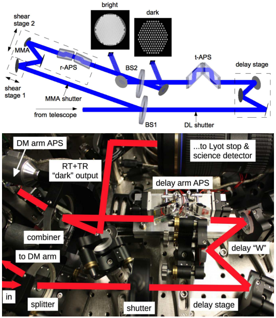
VNC narrowband results - TDEM Milestone #1

SPIE Proceedings: Lyon+ (2012)
TDEM Milestone Report: Clampin+ (2013)



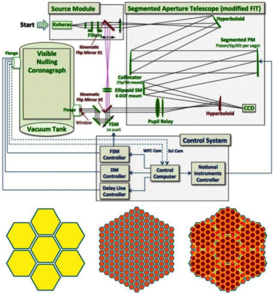
Repeatability and traceability to wavefront control following telescope slew/settle demonstrated with multiple Data Collection Events (DCEs), each starting from scratch over several days

Outline: ongoing & forthcoming VNC development



1) Broadband demo

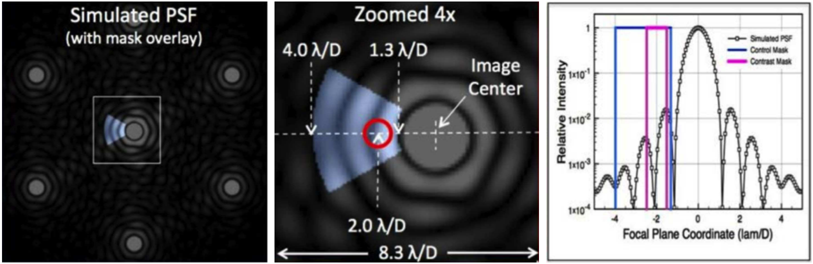
2) Segmented stimulus



1 + 2 = 3) SAINT

VNC broadband demo - TDEM Milestone #2

From Clampin, Lyon, Petrone, Mallik, Bolcar, Madison, and Helmbrecht, *TDEM Milestone #1 Final Report* (2013)



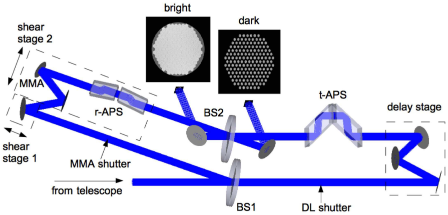
Same as TDEM # 1, but at 1.0×10^{-9} over 40 nm FWHM centered on 633 nm:

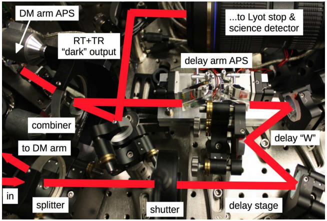
- *Left*: Dark hole region overlay on simulated PSF.
- *Center*: control modes are designed to achieve 10^{-9} contrast over 40 nm bandpass within the wedged region with the circle of diameter $1\lambda/D$ centered at $2\lambda/D$ showing the region over which the contrast is calculated.
- *Right*: plot from left to right along the dashed line in the central panel showing the control mask extending from -4 to $-1.3\lambda/D$.

Broadband VNC Approach

Use Fresnel rhomb retarders as Achromatic Phase Shifters (APS)

- The APS consists of two pairs of symmetric Fresnel rhombs as half wave retarders
- Rhomb pairs are oriented orthogonally to one another in terms of respective s- and p-planes
- APS chromatic leakage must not exceed 10^{-7} rms over 613-653 nm bandpass in order to reach final 10^{-9} averaged over $1\lambda/D$ diameter circular dark region centered at $2\lambda/D$



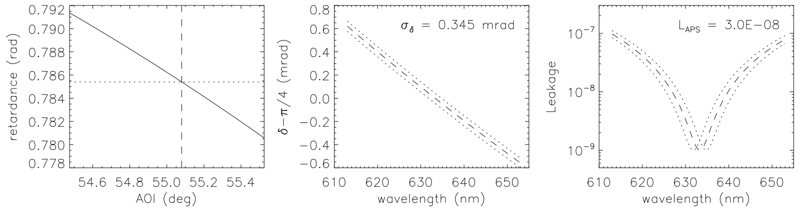


Hicks+, *Proc. SPIE* (2015)

Expected performance of Achromatic Phase Shifter (APS)

Uncoated Fresnel rhombs selected as a buildable approach to meeting the TDEM milestone

Hicks+, *Proc. SPIE* (2015)



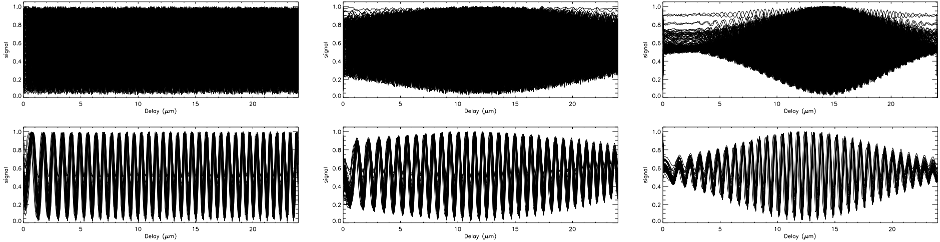
Plots of theoretical BK7/vacuum retardance (δ) optimized for the 613-653 nm bandpass

- *Left:* Retardance as a function of total internal reflection (TIR) angle of incidence (AOI)
- *Center:* Retardance as a function of wavelength at the design AOI
- *Right:* Chromaticity of the null
- Dashed lines correspond to the design AOI, dotted are +/- 15 arcsec

Parallel coronagraphs or alternative approaches needed for achieving deeper nulls over a broader instrument bandpass

Deformable mirror segment phasing: narrowband vs. broadband

- Scan delay line while recording intensity on each segment for fringe packet fitting and determining segment piston and tip/tilt offsets
- Tip/tilt on a given segment reduces fringe visibility
- 1, 40, and 80 nm bandpasses shown from left to right below

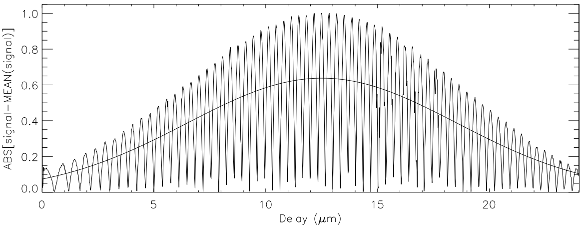


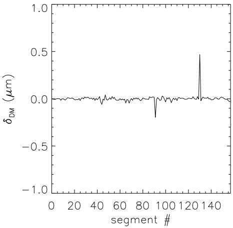
$\frac{\lambda^2}{\Delta\lambda} \approx 400\mu\text{m} \approx 633$ waves

$\frac{\lambda^2}{\Delta\lambda} \approx 10\mu\text{m} \approx 16$ waves

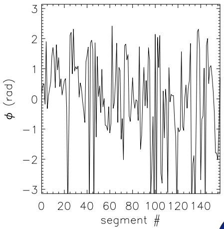
$\frac{\lambda^2}{\Delta\lambda} \approx 5\mu\text{m} \approx 8$ waves

Deformable mirror segment phasing: group and phase delay

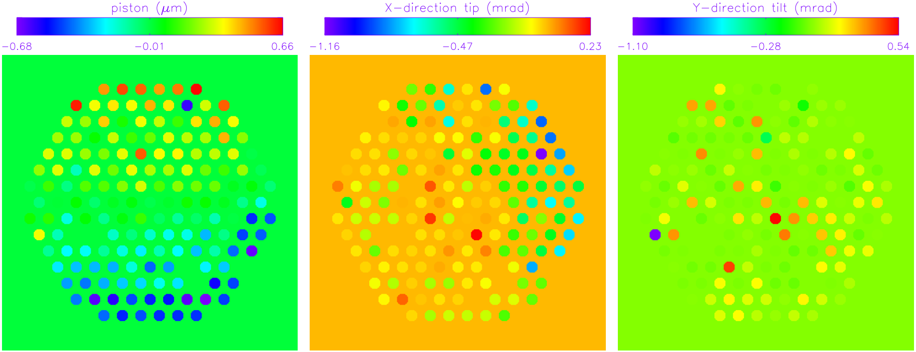




- Fit 3-parameter Gaussian (amplitude, FWHM, offset) to signal modulus for each segment (single scan above)
- Use offset to determine group delay for each segment relative to average (upper right)
- Shift scan data by offset and determine phase residual (lower right)
- Calculate deformable mirror correction to last state vector and iterate

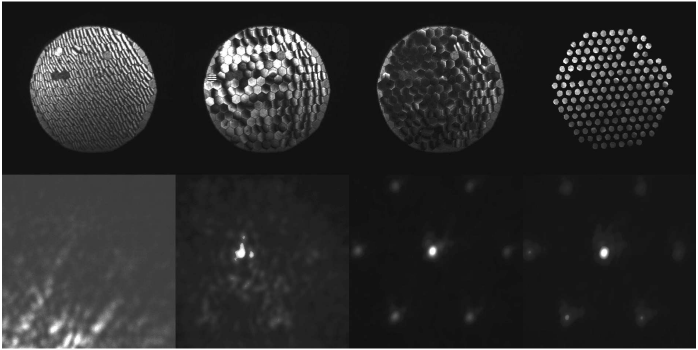


"Flattened" deformable mirror state vector



- Goal is to minimize peak-to-valley of each state vector: piston, tip, tilt
- Top to bottom gradient in piston map indicative of tilt between nuller arms
- Nearest neighbor outliers restrict solution range

DM states visualized in bright pupil and dark focal outputs

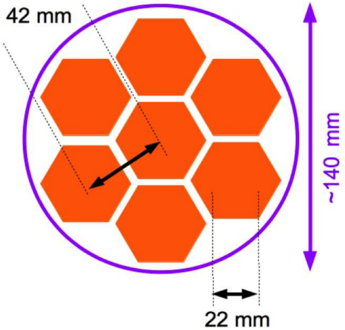


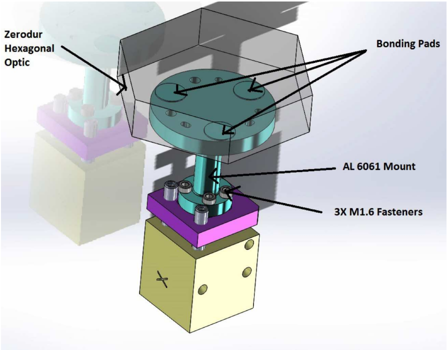
- *Left to right*: DM at system startup, after setting all segment PTT values to 0, following coarse "flattening" (relative to delay arm reference), and additional flattening "by hand"
- The digital mask applied in upper right corresponds to the physical Lyot mask in the dark focal output that produces the characteristic sidelobes visible at $\sim 15\lambda/D$
- Dark outputs are the DM only and normalized to the brightest pixel value

Macro-scale actively controlled segmented mirror array

In development to demonstrate laboratory coronagraph performance in the presence of complex diffraction and instabilities

Rendering provided by C. Koca (NASA GSFC)



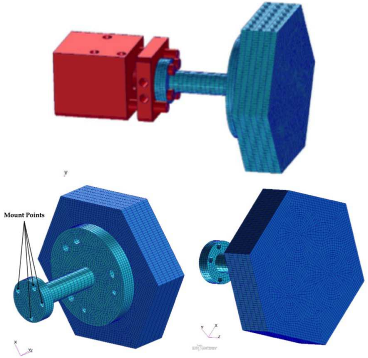


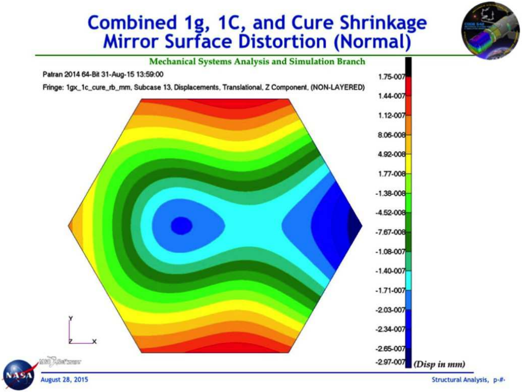
R = 4000 mm, k = 0 surface allows multiple approaches to generating array using parent segmentation or blocking

Finite element analysis of gravity sag, thermal, and bond stress

Including mounted segment surface measurements (+ environment dynamics) will allow scalable STOP model study and tuning of end-to-end active primary + DM wavefront control (forthcoming slides)

	Translation (mm)			Rotation (sec)		
Load Case	X	Y	Z	RX	RY	RZ
1g X	1.523E-03	-1.244E-06	-2.665E-07	0.01	10.07	-0.01
1g Y	-1.244E-06	1.539E-03	3.339E-06	-10.14	-0.01	0.00
1g Z	6.460E-08	3.955E-06	3.587E-05	-0.02	0.00	0.00
1c Bulk Increase	-2.308E-06	-8.468E-06	7.099E-04	-0.03	-0.01	0.00
Bond cure shrink	-8.297E-10	1.904E-10	-2.009E-03	0.00	0.00	0.00

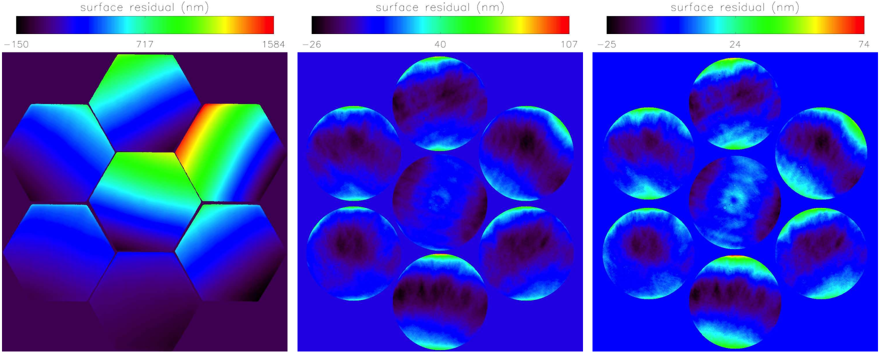




Slide content courtesy of J. Bolognese (NASA GSFC)

Surface residual measurements

Preliminary analysis of unblocked segment quality assurance data



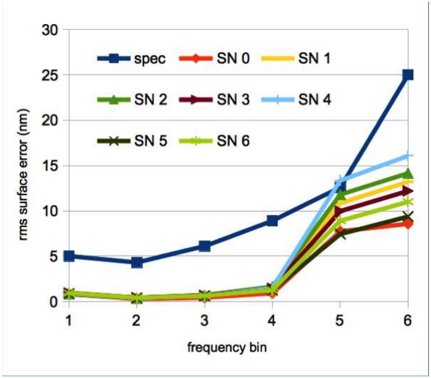
- *Left*: Stitched segment data
- *Center, Right*: Piston/tip/tilt removed and 5, 10 pixel guard band, respectively
- Blocking stress corresponding to asymmetries in blank dimensions – needs more forensics

Surface errors binned by spatial frequency

Charts and table generated from vendor measurements of unblocked segment

bin	wavelengths (mm)	spatial frequencies (cpa)
1	4.0–8.0	5-10
2	8.0–10.0	4-5
3	10.0–13.3	3-4
4	13.3-20.0	2-3
5	$> 20.0^*$	$< 2^*$
6	total*	$< 10^*$

[a] piston, tip, tilt, and power removed



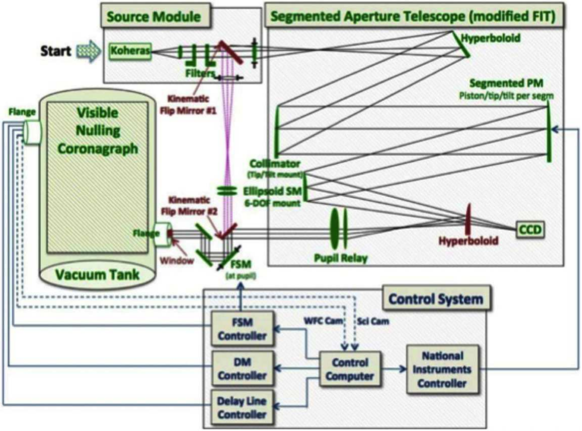
- Surface data taken with 100 mm Zygo and bandpass filtered
- Excellent results surpassing mid–high spatial frequency requirements
- Only a single out of spec point measured in the < 2 cpa bin, likely due to springing

Assembled mechanisms and fit-checking the array

- Design (optics, mounts, fixtures) completed early spring 2015, PO submitted 6/5/2015, mirrors received 11/3/2015, bonding process underway
- Tolerancing of segments and jig to achieve < 0.25 mm segment centration and $< 0.5°$clocking
- Coarse (manual) and fine (active) actuation stages tested
- Combined mirror + pedestal mass less than half recommended actuator load limit

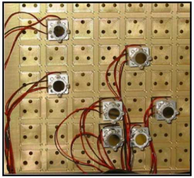
Segmented Aperture Interferometric Nulling Testbed (SAINT)

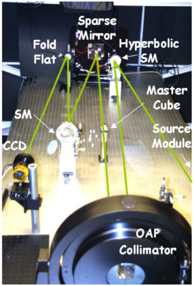
- PI: R. Lyon - Awarded in 2014; Funding initiated 2015
- Demonstrate and quantify high contrast imaging capability with an actively controlled segmented aperture by modifying an existing reconfigurable sparse aperture
- Maintain single mode fiber source option currently used with the VNC
- Fast steering mirror to be added between the segmented aperture telescope and VNC
- Continue incremental improvements to control routines, as well as hardware including detectors, deformable mirror(s), and nuller mechanisms



Adapting the Fizeau Interferometry Testbed (FIT) to SAINT

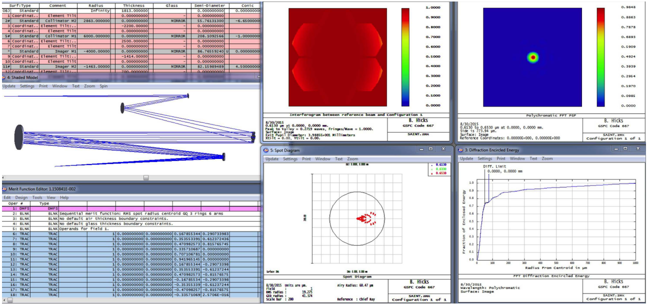
FIT sparse aperture



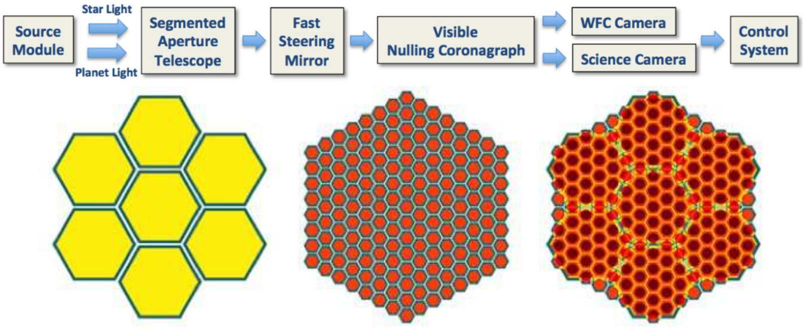


Lyon+, *Proc. SPIE* (2004)

- Filled hexagonal array is a drop-in replacement for sparse array
- Additional hyperbolic mirror before reaching relay collimator
- Periscope relay through baffled vacuum chamber window (not shown)
- Relay reimages segmented primary to fast steering mirror at existing VNC breadboard aperture stop location

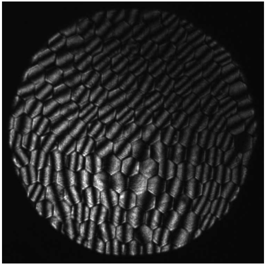
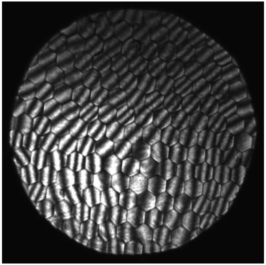
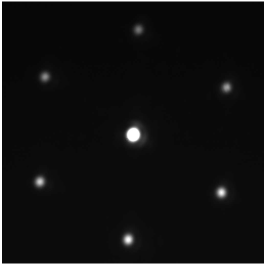


A tool for studying end-to-end controls in the presence of dynamic instabilities



- Refine wavefront control offloading of non-common vs. common mode dynamic perturbations
- Study contrast control authority in the presence of diffraction from a complex aperture
- Mapping of primary segments to deformable mirror segments and Lyot mask

A 100% yield Iris, AO PTT489 DM is available for use with SAINT

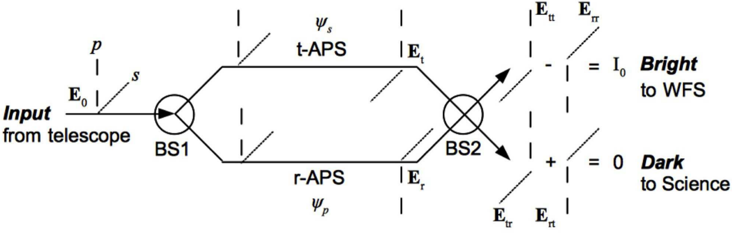
- *Left and center:* APS-equipped 1 nm and 40 nm bandpass VNC bright output pupil images recorded June 2015 using a fully active PTT DM prior to flattening (shown without digital mask)
- *Right:* Broadband PSF of the reference (delay) arm showing the six sidelobes spaced at 60°characteristic of the 7-ring hexagonal array of circular subapertures in the physical Lyot mask

Summary of ongoing and forthcoming VNC development

- Complete the broadband VNC demonstration (imminent)
- Align segmented mirror and generate surface map of phased array (end of calendar 2015)
- Install 100% yield deformable mirror (early 2016 or sooner)
- Finish SAINT telescope, telescope to VNC relay design, and procure components (spring 2016)
- Design the Next Generation Visible Nulling Coronagraph (summer 2016)
- Couple active segmented telescope to VNC, demonstrate SAINT (fall 2016)
- Continue testing of single mode fiber bundle arrays for full field complex wavefront control
- Continue work towards integrating photon counting CCDs and developing detector electronics [Mallik+ *Proc. SPIE* (2015)] using real-time Linux

Backup Slides

Polarization Nulling: *generalized* beamsplitters and retarders



$$\mathbf{E}_0 = E_0 \begin{pmatrix} \cos\theta \\ \sin\theta \end{pmatrix} \qquad \mathbf{E}_t = E_0 \begin{pmatrix} t_\perp e^{i\psi} \cos\theta \\ t_\parallel \sin\theta \end{pmatrix} \qquad \mathbf{E}_r = E_0 \begin{pmatrix} r_\perp e^{i\xi_\perp} \cos\theta \\ r_\parallel e^{i(\psi+\xi_\parallel)} \sin\theta \end{pmatrix}$$

$$\mathbf{E}_{tt} = E_0 \begin{pmatrix} t_\perp^2 e^{i\psi} \cos\theta \\ t_\parallel^2 sin\theta \end{pmatrix} \qquad \mathbf{E}_{rr} = E_0 \begin{pmatrix} r_\perp^2 e^{i2\xi_\perp} \cos\theta \\ r_\parallel^2 e^{i(\psi+2\xi_\parallel)} sin\theta \end{pmatrix} \qquad I_b = |\mathbf{E}_{tt} + \mathbf{E}_{rr}|^2$$

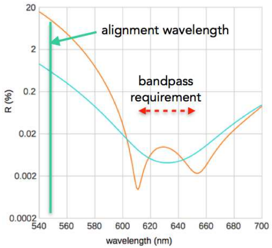
$$\mathbf{E}_{tr} = E_0 \begin{pmatrix} t_\perp r_\perp e^{i\psi} \cos\theta \\ t_\parallel r_\parallel \sin\theta \end{pmatrix} \qquad \mathbf{E}_{rt} = E_0 \begin{pmatrix} r_\perp t_\perp \cos\theta \\ r_\parallel t_\parallel e^{i\psi} \sin\theta \end{pmatrix} \qquad I_d = |\mathbf{E}_{tr} + \mathbf{E}_{rt}|^2$$

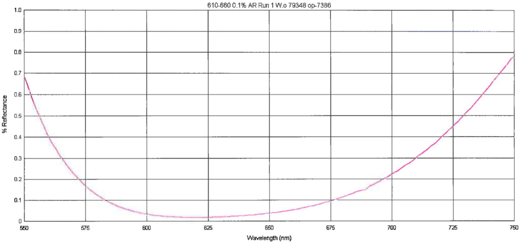
APS specifications and measurements

	Specification	Measurement				Comment
		FR1	FR3	FR8	FR10	
Thickness	12.3+00/-0.05 $\pm$20 nm precision	12.28323	12.28323	12.28314	12.28314	FR1 pairs with FR8, FR3 pairs with FR10
Length (unchamfered)	35.24+0.0/-0.1 $\pm$50 nm precision	35.20	35.20	35.24	35.24	Precision specification not met
Entrance/exit edge length	15.0+0.0/-0.1	14.95$\pm$0.01				
Angle	55°4'48$\pm$1.0"; $\pm$0.1 precision	55°4'48.5"$\pm$0.5"				Measurement performed optically contacted to machining reference chuck
TIR surface parallelism	$<$ 0.5; $\pm$0.1 precision	0.12	0.17	0.20	0.15	
Entrance/exit parallelism	$<$ 0.5; $\pm$0.1 precision	1.6	0.7	5.0	2.8	Calculated from transmitted beam deviation at 633 nm
Right angle errors	$\pm$1.0' from 90°	$<$ 0.5'	$<$ 1.0	$<$ 1.0	$<$ 0.5	
P-V WFE	$<$ 43 ($< \lambda/15$ at 633 nm)	12, 20, 10, 11	11, 24, 12, 9	16, 31, 10, 17	21, 14, 10, 24	F, B, T, U surfaces
RMS WFE	$<$ 13 ($< \lambda/50$ at 633 nm)	2, 4, 1, 2	1, 4, 2, 1	3, 4, 1, 3	4, 2, 1, 4	F, B, T, U surfaces
P-V WFE	$<$ 159 ($< \lambda/4$ at 633 nm)	103 114	95 109	155 109	122 93	R, L alignment surfaces
RMS surface roughness	$<$ 1		0.8 (F)	0.9 (F), 0.8 (B)		
Scratch/Dig	10/5	10/5				
Entrance/exit reflectance	$R_{avg} < 0.1\%$, 613-653 nm	$<$ 0.1%				

- Dimensions in mm, angles in arcseconds, and surfaces in nm unless specified

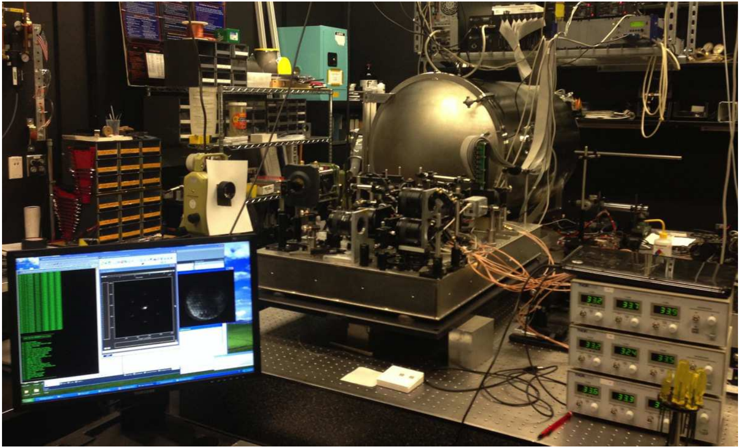
Rhomb anti-reflection coatings





- Require $R < 0.1\%$ over design bandpass
- Reflectance can be enhanced to aid in alignment

The Visible Nulling Coronagraph (VNC) laboratory



Optics and detectors, control software and electronics, and vacuum isolation chamber

WFC sequence