The hybrid Lyot coronagraph for the AFTA telescope

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Meeting of the AFTA Coronagraph Working Group
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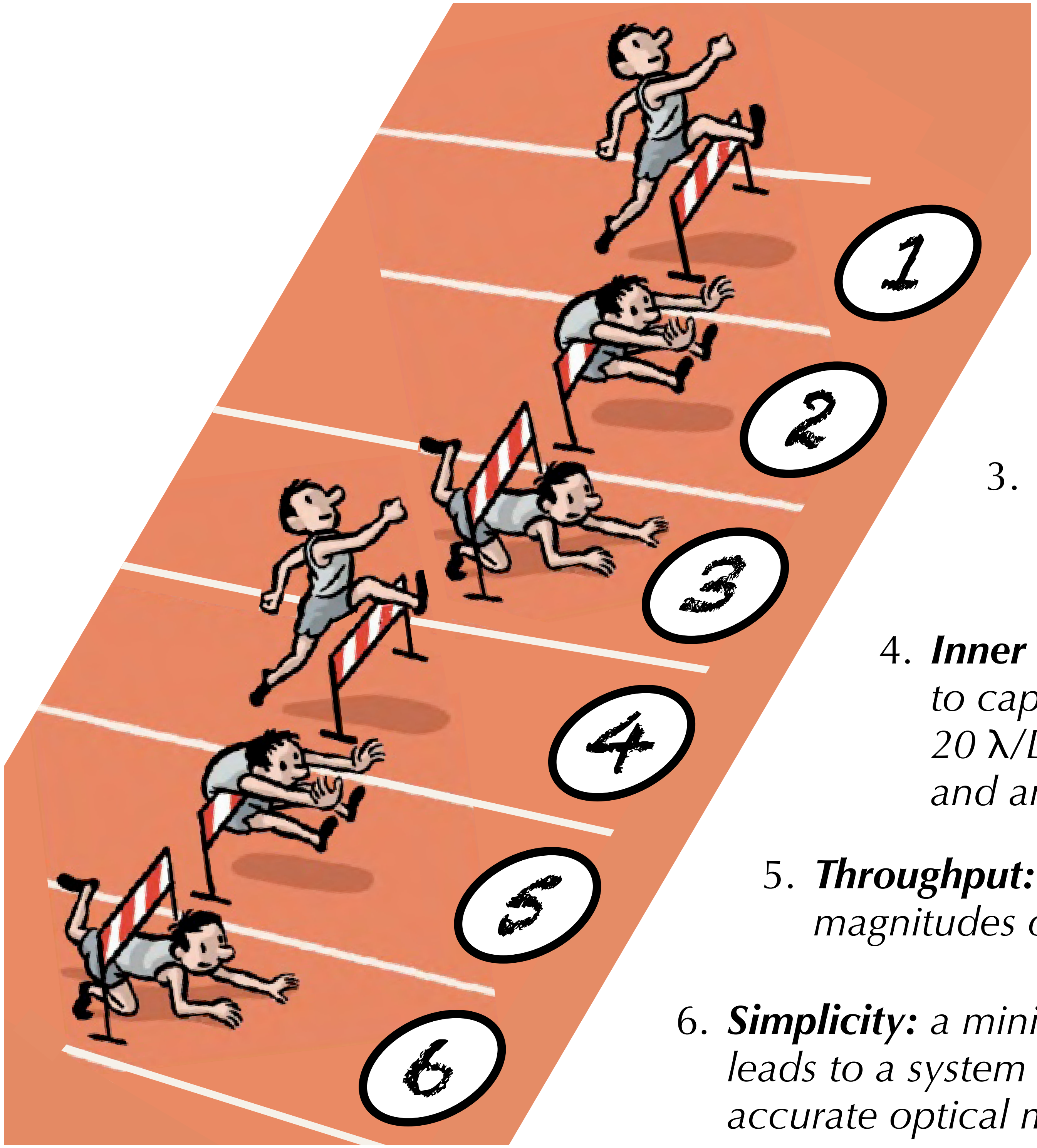
Direct Imaging Coronagraph – Technical Objectives



1. ***Raw contrast better than 10^{-9}:*** *Exoplanets are 10^{-9} or fainter than the central star in reflected starlight. This is beyond the reach of large ground based telescopes, which are expected to achieve contrasts to 10^{-8} in the coming decade.*

2. ***Pointing error tolerance*** *that preserves contrast performance with pointing jitter and stellar diameters of order 1 milliarcsecond.*

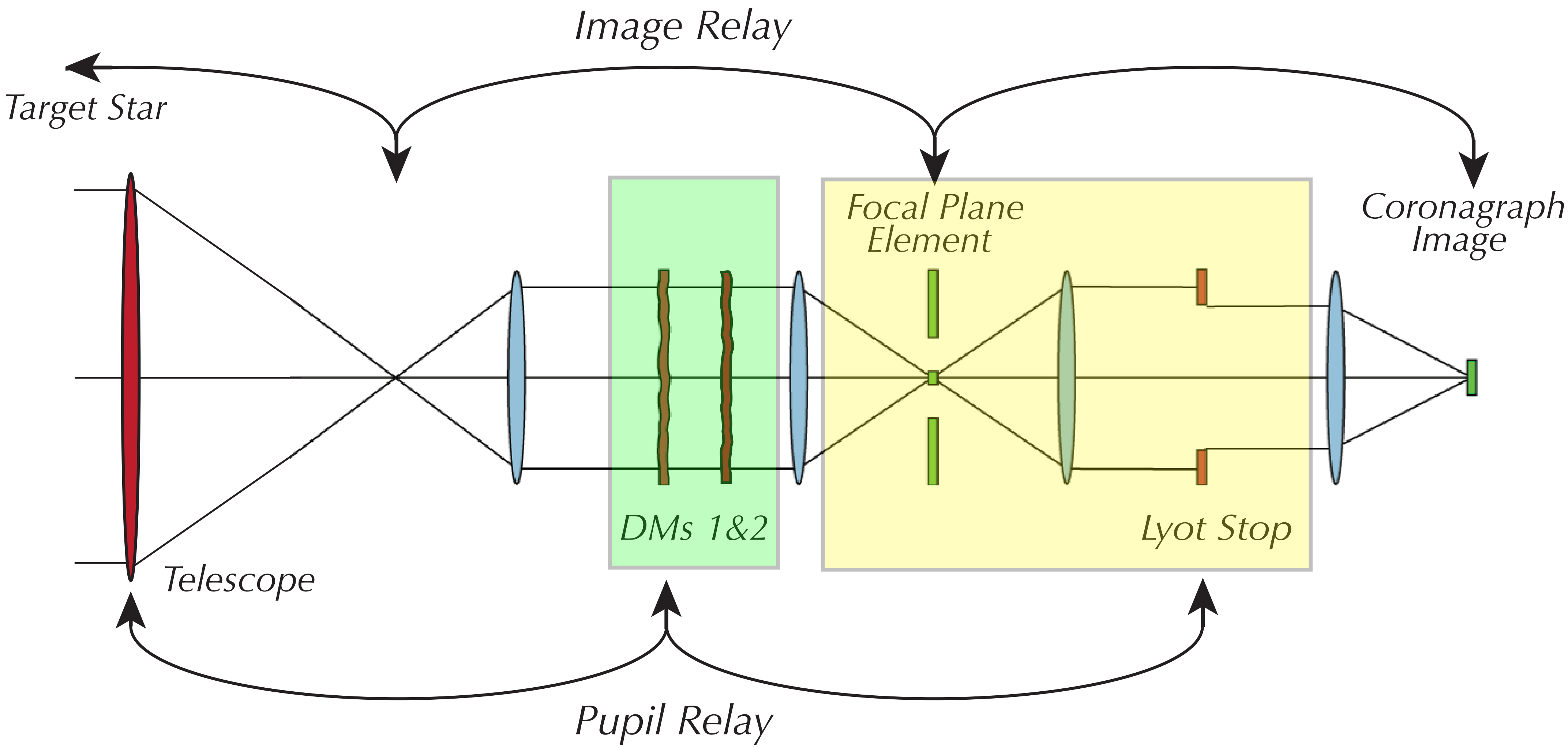
3. ***Spectral bandwidth:*** $\delta\lambda/\lambda$ *greater than 10% – bandwidth needed to capture scarce photons and enable color photometry and spectroscopy.*

4. ***Inner and outer working angles:*** *3 λ/D or closer to the star to capture significant numbers of exoplanets, extending to 20 λ/D or more to cover exoplanet systems, debris disks, and analysis of background objects.*

5. ***Throughput:*** *better than 30% – exoplanets are faint, with visual magnitudes of 23-30 in reflected starlight.*

6. ***Simplicity:*** *a minimum number of critical elements and alignments leads to a system with reduced cost and risk, greater overall efficiency, accurate optical models, and reliable performance predictions.*

Essential elements of the Lyot coronagraph

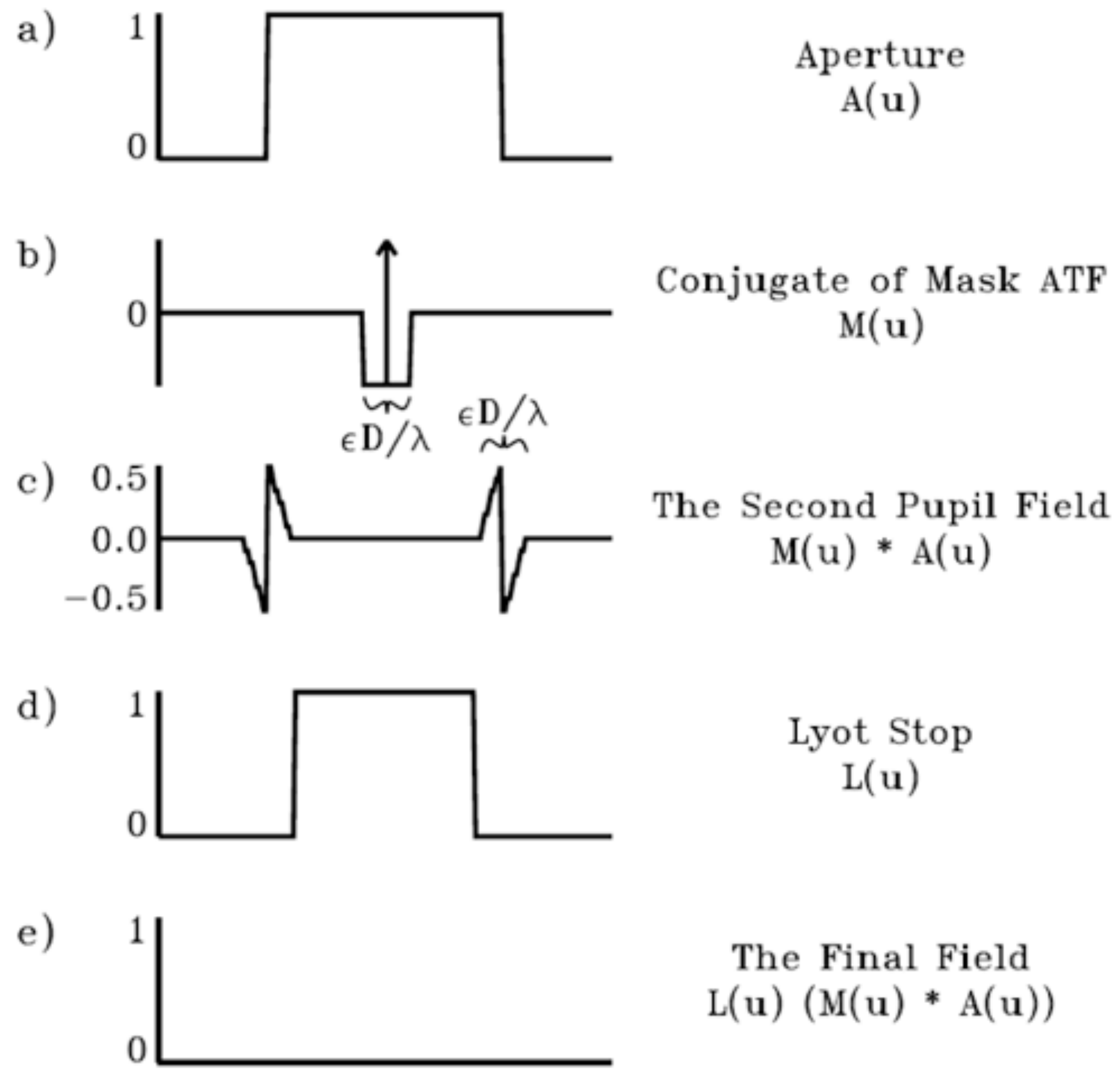


- This **actively corrected Lyot-type coronagraph** layout is compatible with number of major coronagraph types (hybrid Lyot, vector vortex, shaped pupil).
- Wavefront is controlled with a **sequential pair of deformable mirrors** in the collimated beam upstream from the coronagraph.
- Diagram unfolds the optical system and depicts powered elements as lenses for clarity.
- Coronagraph elements are highlighted in yellow, wavefront control elements in green.

Simplicity favors the Lyot coronagraph

- ***Minimum number of critical optical elements*** *(6) between the star and coronagraph that are subject to* ***super-tight*** *wavefront control, beam walk, polarization effects.*
- *Minimum optical elements favors* ***higher throughput*** *and* ***fewer critical alignments****.*
- *There are* ***no high-angle reflective elements****, minimizes polarization effects internal to the coronagraph.*
- *There are* ***no transmissive elements*** *upstream of the focal plane occulter, i.e., there are no apodizers or polarizers, avoids dispersion.*
- *The* ***critical apodization is captured*** *on a small occulting mask, which is one metal and one dielectric thin film layer on a glass substrate, stable and robust for flight.*
- ***No optical distortions*** *are introduced from sky to science focal plane, simplifies iterative wavefront sensing and control.*
- ***End-to-end optical propagation calculations*** *(Fresnel approximation) and* ***system optical tolerancing*** *are relatively straightforward.*
- ***Minimizes complexity!!*** *Parts count, engineering interfaces, mutual alignments snowball in the buildup of assembly fixtures and metrology, alignment tolerances, failure modes and risk analysis, engineering coordination and reviews, subsystem integrations and tests – and these ultimately increase the cost, mass, schedule, and overall risk of the instrument implementation.*

The Band-Limited Coronagraph



Kuchner and Traub (2002)

Next step: hybrid Lyot coronagraph

$$A_{REAL} = \max(10^{-4}, A_S), \textit{ where } A_S(x) = 1 - \left(\frac{\sin(\pi x/w)}{(\pi x/w)} \right)^2$$

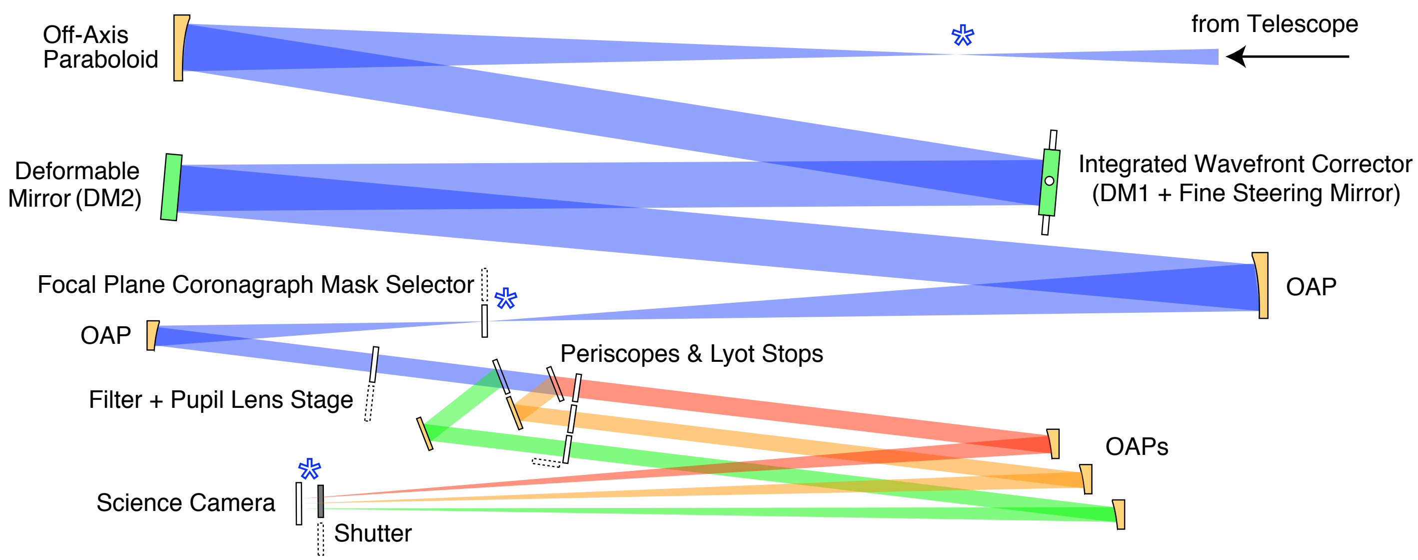
$$A_{IMAGINARY} = \alpha \left(\frac{\sin(\pi x/w_1 + \pi)}{(\pi x/w_1 + \pi)} \right) + \alpha \left(\frac{\sin(\pi x/w_1 - \pi)}{(\pi x/w_1 - \pi)} \right)$$

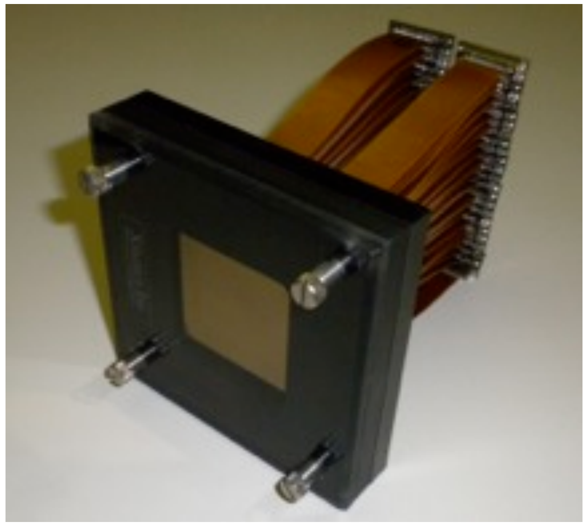
$$OD_{metal+dielectric}(x) = -2 \log_{10} \left\| A_{REAL} - jA_{IMAGINARY} \right\|$$

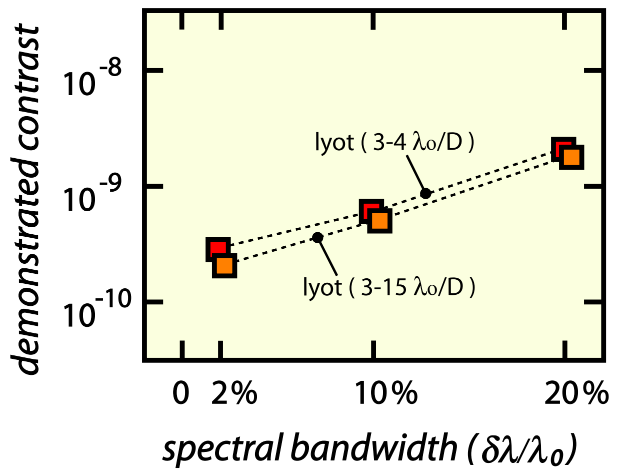
$$\delta\, phase_{metal+dielectric}(x) = phase\left(A_{REAL} - jA_{IMAGINARY}\right)$$

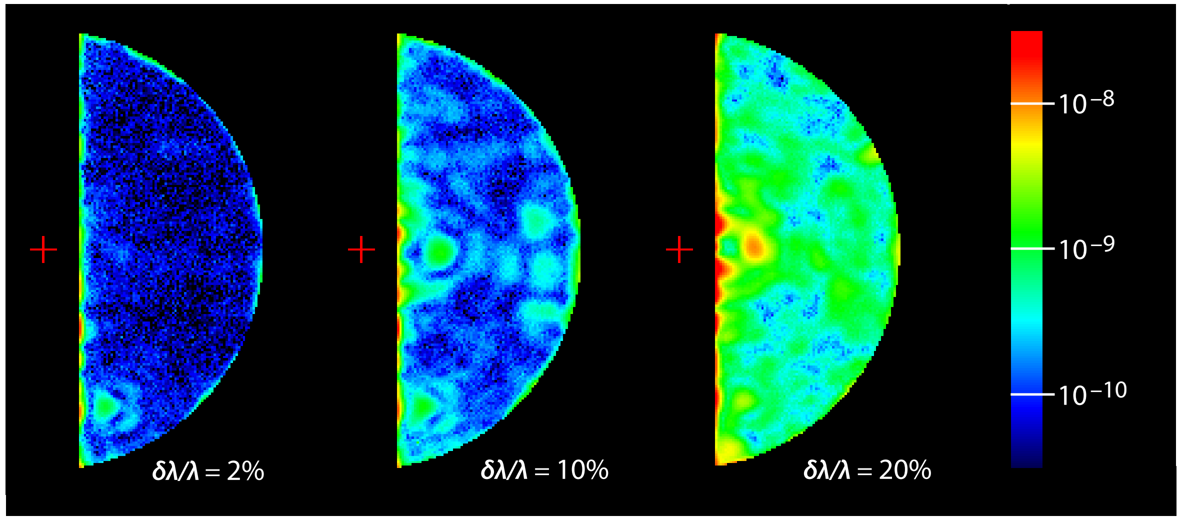
- *Example: analytic band limited Lyot for an unobscured telescope aperture.*
- *Objective is an occulter that is **band limited in both real and imaginary parts**.*
- *Real part is ~sinc-squared, imaginary part is a family of curves for -0.49 < α < 0.49.*
- ***Monochromatic solution is exact**, provides a good starting point for broadband.*
- ***Broadband optimization** requires compromise between band-limited ideal and the physical effects of dispersion.*
- ***Optimization code** performs dark field nulling while regarding the metal and dielectric profiles as free parameters, varying simultaneously with the DM setting.*

Coronagraph configuration for an unobscured telescope







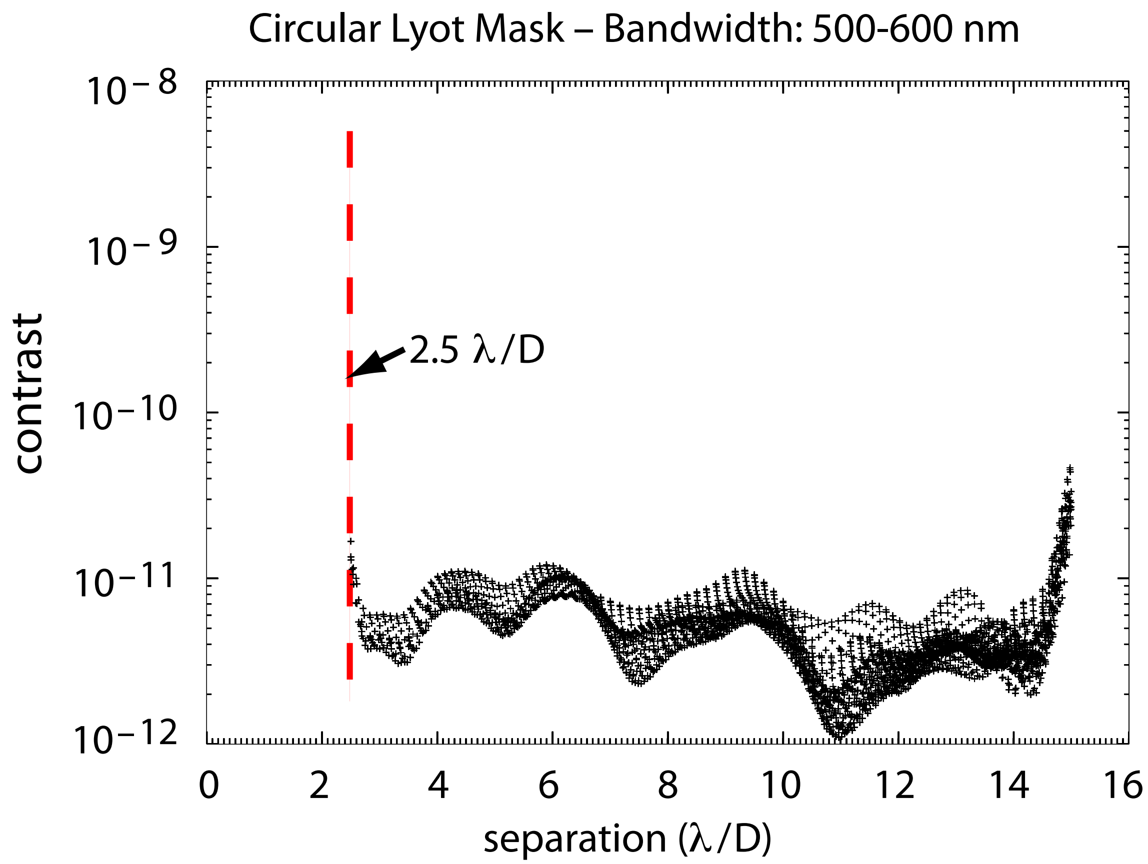


- ***ACCESS optical layout*** *is functionally similar to the AFTA coronagraph.*
- *A pair of* ***protoflight qualified deformable mirrors*** *(a 48x48 actuator DM is shown) manipulate the wavefront amplitude and phase to create a high contrast dark field.*
- *Representative* ***Lyot coronagraph*** *raw contrast performance, as demonstrated in the NASA SAT/TDEM program, is used to forecast ACCESS mission performance with post-processing of images.*

Unobscured telescope apertures are preferred for high contrast coronagraphy

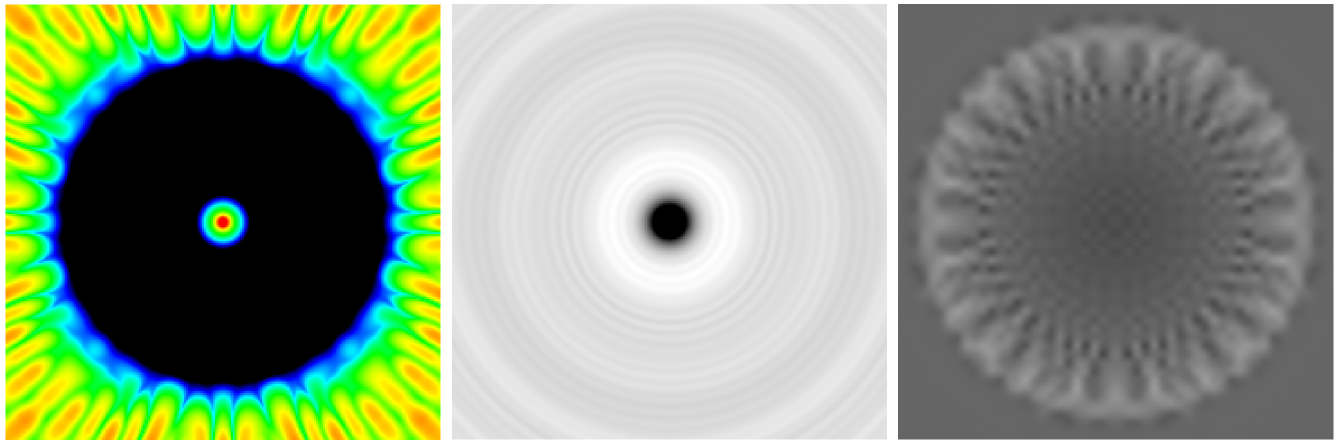
Complex Apodization Lyot Coronagraphy

John Trauger, Brian Gordon, John Krist, Dimitri Mawet, Dwight Moody (Proc.SPIE 8442-04, 2012)



Computed performance for a newly designed circular complex apodized Lyot mask:

- *As for previous linear mask designs, the thickness profiles of the metal and dielectric layers are optimized simultaneously with the wavefront phase control of a single 48x48 DM.*
- *Focal plane mask is a layer of nickel plus a layer of cryolite superimposed on a fused silica substrate.*
- *These two layers provide the degrees of freedom to control both the real and imaginary parts of the optical wavefront.*
- *Inner working angle is 2.5 λ_0/D. Note that a full 360^{O} dark field has been created with a single deformable mirror.*
- *Contrast in the 500-600 nm ($\delta\lambda/\lambda_0 = 18\%$) spectral band is 5.3×10^{-12} in both the inner 2.5–3.5 λ_0/D annulus and averaged across the entire dark field extending from radii of 2.5 to 15 λ_0/D.*



Left: Raw contrast in the dark field is displayed with a logarithmic stretch from 10^{-11} to 10^{-7}.

Center: Intensity transmittance profile of the complex apodized focal plane mask is displayed with a linear stretch from zero to 1.

Right: Corresponding surface setting on the deformable mirror is displayed with a linear black-to-white stretch of 40 nm.

Coronagraph design trade space

- ***Global optimization of the coronagraph system**: we include as free parameters:*
  - *Thickness profiles on the focal plane occulting mask (metal & dielectric layers)*
  - *Shape and dimensions of the Lyot stop*
  - *Surface figure settings on each of the two DMs*
- ***Design trade metrics:** defined by the foregoing performance objectives:*
  - *Raw image contrast, better than 1e-8*
  - *Pointing error tolerance > 1 milliarcsec*
  - *Spectral bandwidth > 10%*
  - *Inner and outer working angles, IWA < 3 lambda/D*
  - *Overall throughput > 30%*
  - *Engineering simplicity*
- ***Question for the ExEP/SDT/TAC !***
  - *Given a coronagraph that meets the MUST requirements, what figure merit will be used in evaluating WANTS coronagraph performance enhancements?*

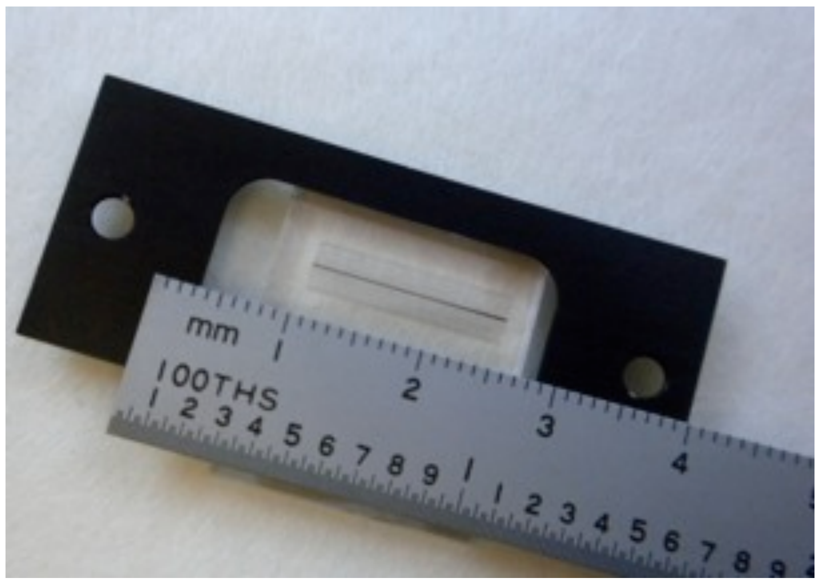
Coronagraph design optimization

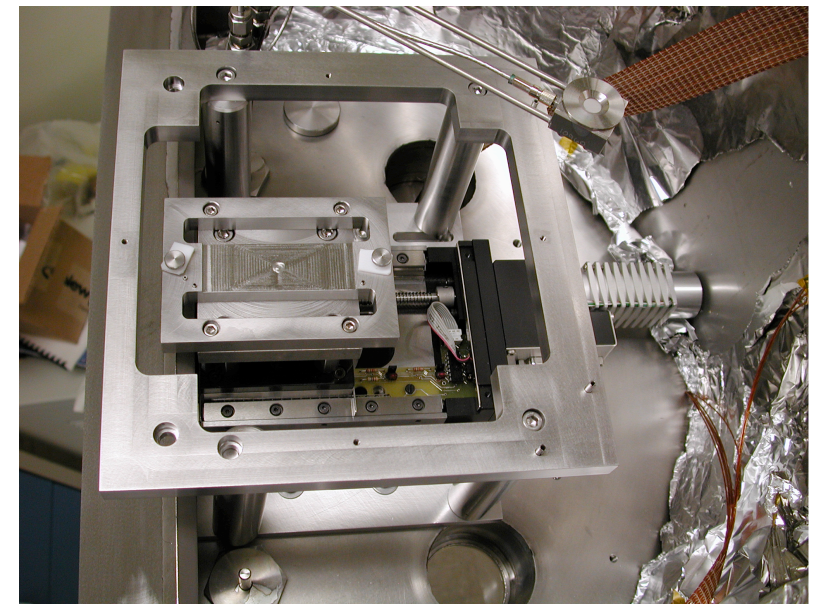
- ***Non-linear least squares optimization:***
  - *Focal plane and pupil plane masks and DM settings as free parameters*
  - *Iterative, small linear steps, method of steepest descent, parameter regularization*
- ***Design constraints:***
  - *Circular symmetric metal-dielectric hybrid Lyot focal plane occulter*
  - *AFTA 2.4 meter telescope (as supplied by John Krist on 8/21/13, with offset circular central obscuration, six SM support struts, zero surface figure and alignment errors)*
  - *Wavefront control with a pair of 48x48 DMs in series*
  - *Inner working angle = 3* λ/D *(142 milliarcsec with 2.4 meter telescope)*
  - $\delta\lambda/\lambda$ = *10% spectral bandwidth centered at* λ = *550 nm*
  - *1 millliarcsec stellar diameter (~angular diameter of the sun at 10 pc)*

Coronagraph design optimization, continued ...

- ***Optimization goals:***
  - *High contrast, foregoing design trade metrics, minimal DM stroke.*
  - *Figure(s) of merit for coronagraph performance as defined by the AFTA TAC.*
- ***Optimization utilizes the available degrees of freedom in successive phases:***
  - *Adjust free parameters in an optimal sequence and in small linear steps*
  - *Pupil representation progresses from unobscured circular pupil, then adds central obscuration, then adds struts*
  - *DM settings progress from single DM, then two DMs with simple rules, then two DMs with numerically optimized settings.*

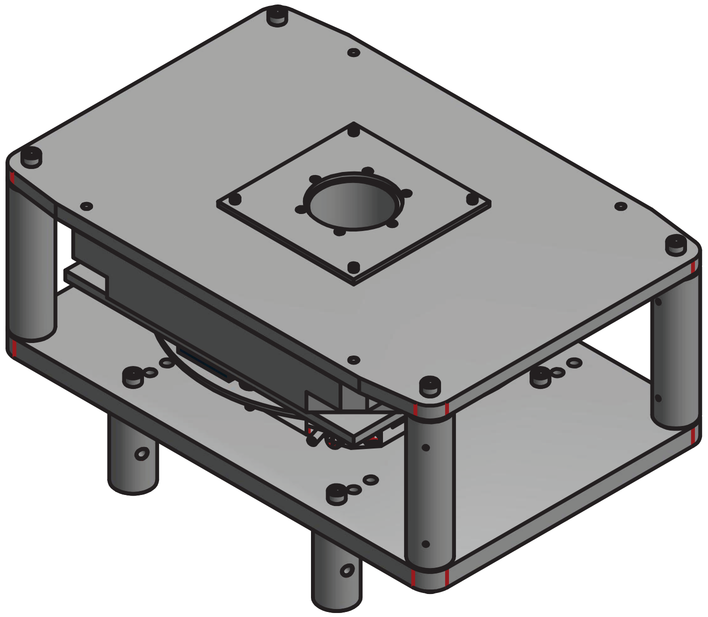
Occulter Fabrication – linear masks

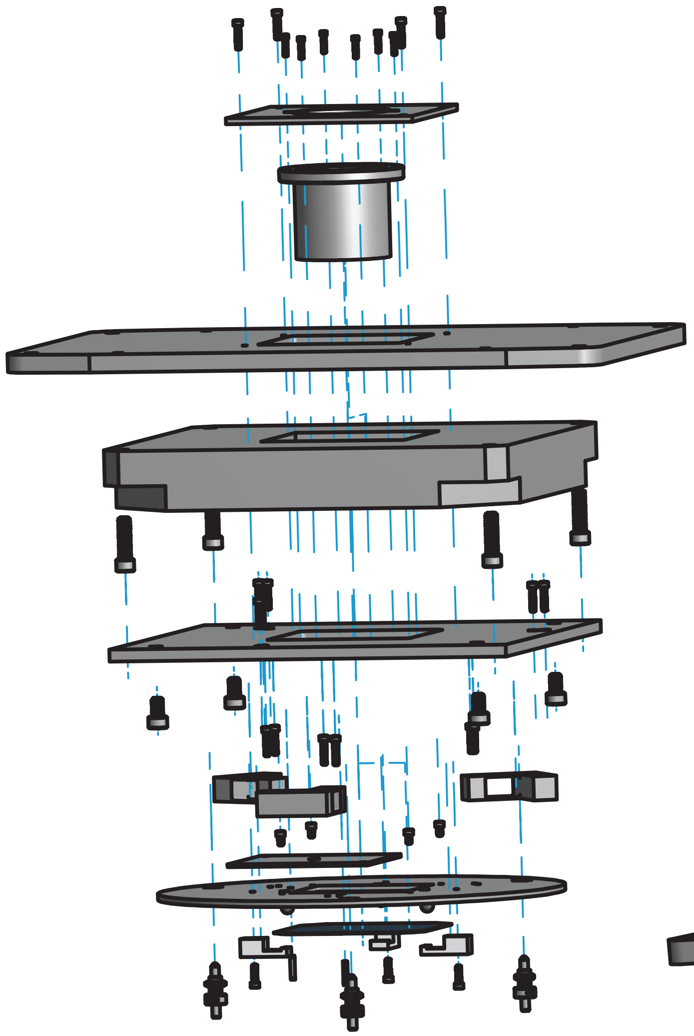


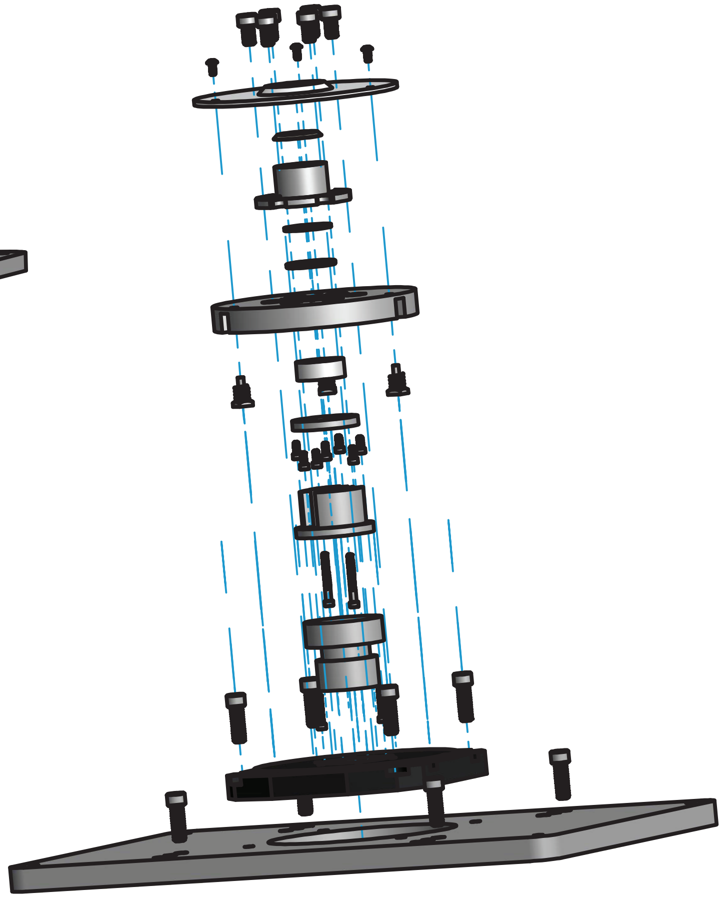


- *Profiled metal and dielectric thin films are vacuum deposited on a glass substrate.*
- *Vacuum deposition through a 15 micron slit (slit is made at JPL's MDL).*
- *Substrate is scanned in 1 micron steps behind the slit during deposition, dwell times define the thickness profiles.*
- *Mask performance has been validated in the coronagraph laboratory.*
- *Finished masks are stable and robust, a suitable technology for flight.*

Occulter Fabrication – circular masks



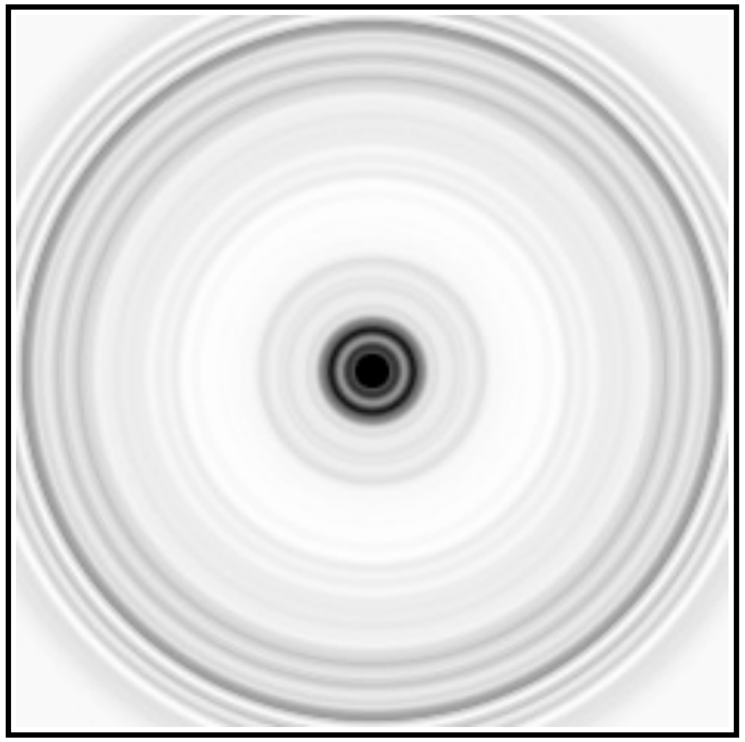




- *Again, profiled* ***nickel*** *and* ***magnesium fluoride*** *thin films are vacuum deposited on a glass substrate.*
- ***New deposition fixture*** *rotates the glass substrate, uses an x/y positioner for microstencil selection, and again dwell times x deposition rate define the thickness profiles.*
- *Vacuum deposition through a set of circular/annular microstencils (made at JPL's MDL).*
- *Finished masks will be stable and robust,* ***a suitable technology for flight****.*

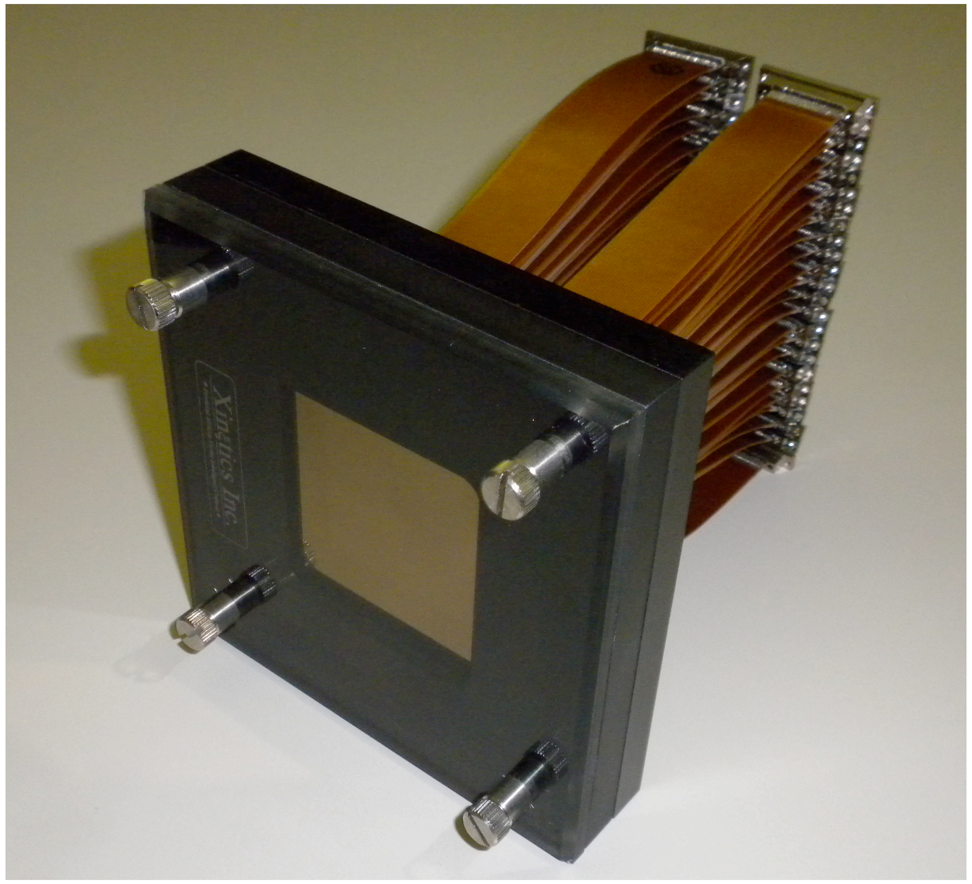
Global optimization: focal plane and pupil plane elements

- *Metal-dielectric (nickel and MgF2) focal plane mask controls both the real and imaginary parts of the star's point spread function. The intensity transmittance is illustrated here.*
- *Pupil plane (Lyot) mask has cutouts for the central obscuration and the six support struts. Lyot throughput is 37%.*



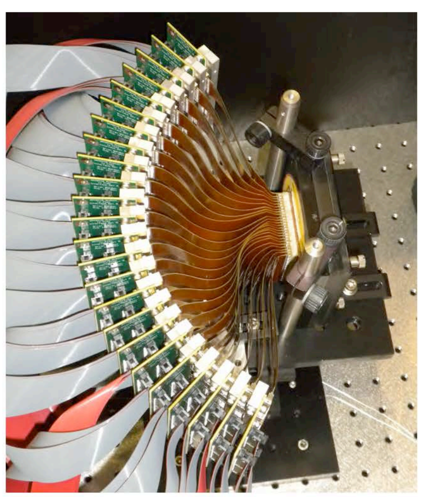
Focal Plane Element

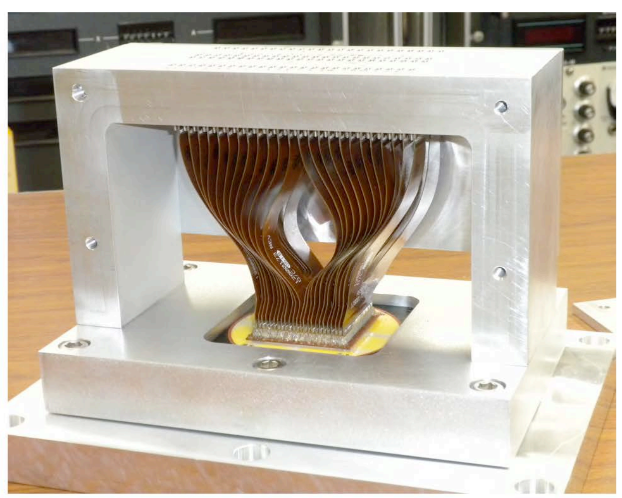
Pupil Plane Element



Measured DM characteristics are the basis for wavefront control

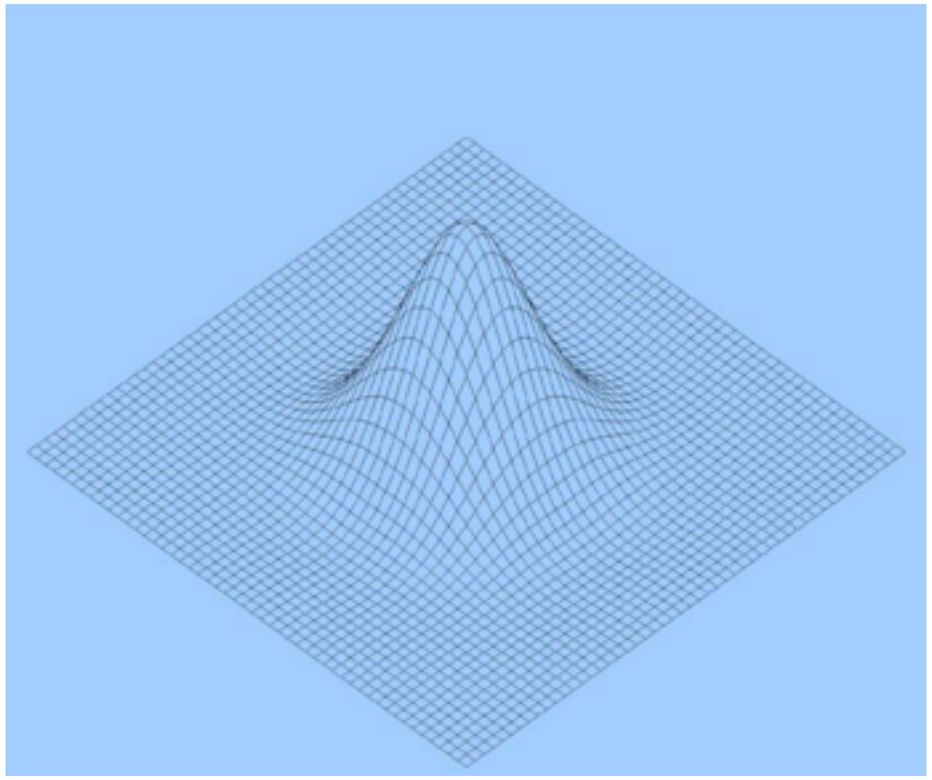
- *Shown is a **48x48 actuator** PMN electrostrictive deformable mirror.*
- *This DM is flight-ready, has completed a **protoflight qualification** 3-axis vibe test to 10.8 grms.*
- *Mirror facesheet is fused silica polished flat to **5 nm rms surface** figure in the unpowered state.*
- *On the backside, a 50x48 pin grid header provides electrical connections to each of the 2304 actuator elements.*
- *Flex circuits carry the interconnects to 48 flight-quality 51-pin connectors.*
- *Manufactured by AOA Xinetics.*

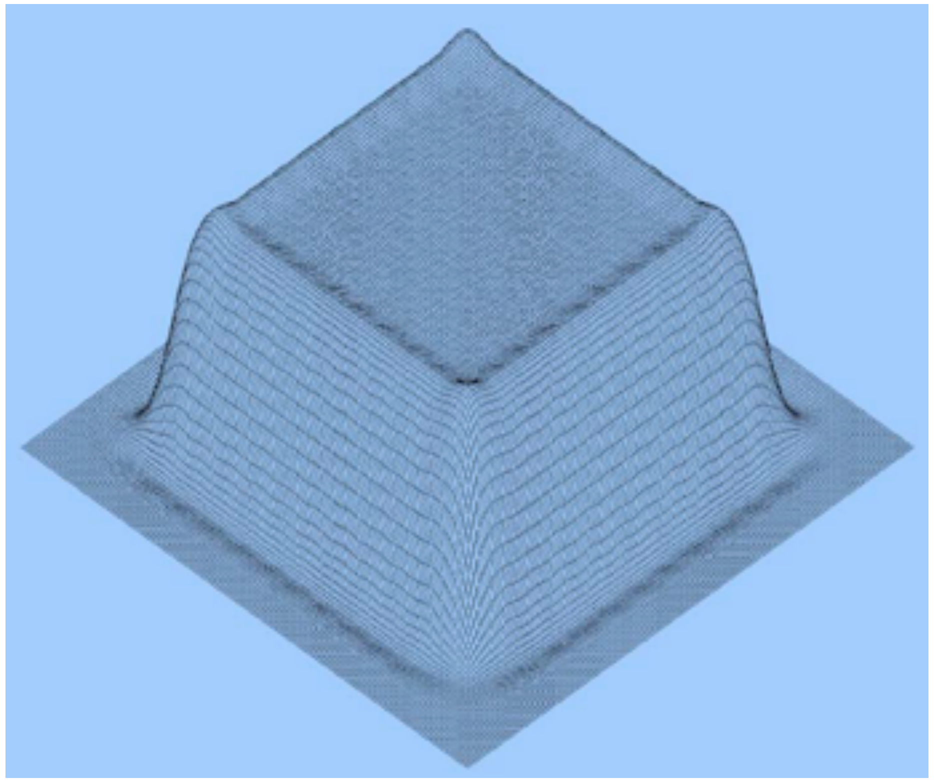




- *Above, the 48x48 DM is mounted on the Zygo bench for optical tests. Flex ribbon cables fan out to the 2304-channel electronic driver system.*
- *Above right, the DM is clamped into its shake test fixture, with all flex connectors anchored as shown, prior to adding shear plates, ready for 3-axis random vibe tests.*

Measured DM influence functions





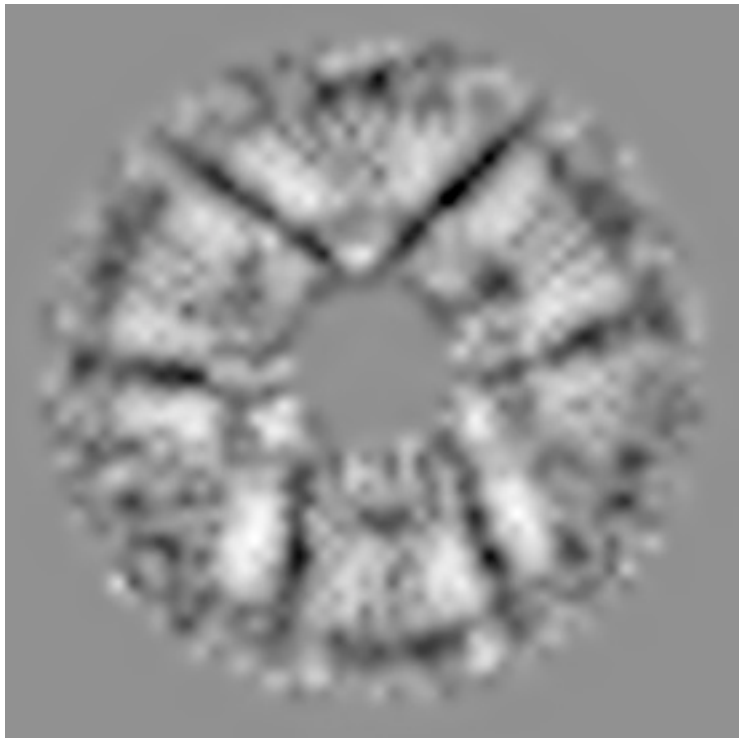
- *At left, the **surface influence profile** for a single actuator. Surface displacement relaxes typically to 10% of the central displacement at the nearest neighboring actuators (1 mm away).*
- *Actuator pitch is 1/mm, surface profile has been measured in a vacuum interferometer with 0.1 x 0.1 mm sample density.*
- *At right, **linear superposition** of individual influence functions predicts overall DM surface displacement: shown is the surface figure result for the simple addition of an 11x11 array of actuator influence functions.*

Global optimization: wavefront control & Lyot stop

- *Shown here, the wavefront phase modulations introduced by the two 48x48 DMs with the foregoing occulting and Lyot masks. PV surface displacements are 0.6 μm.*
- *Note that these DM settings show a similarity to the ACAD strategy (Pueyo). In fact, the pair of DMs can compensate entirely for the diffraction from the six struts using a circular symmetric Lyot stop (w/o cutouts for the struts), but this would require an undesirable large ~5 μm PV of DM surface displacement.*

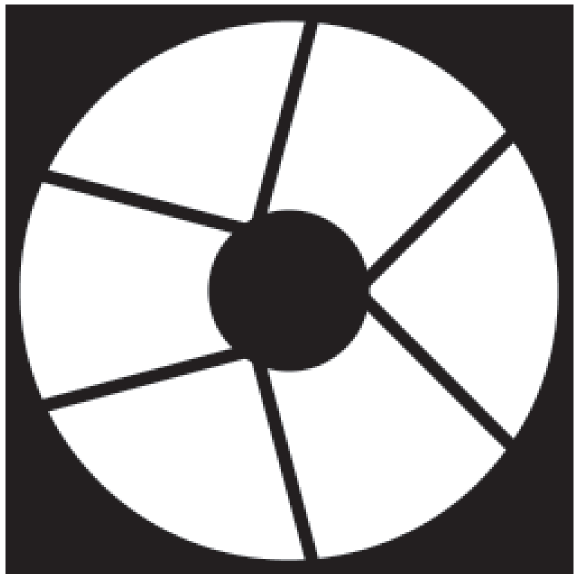
Lyot stop (blue)

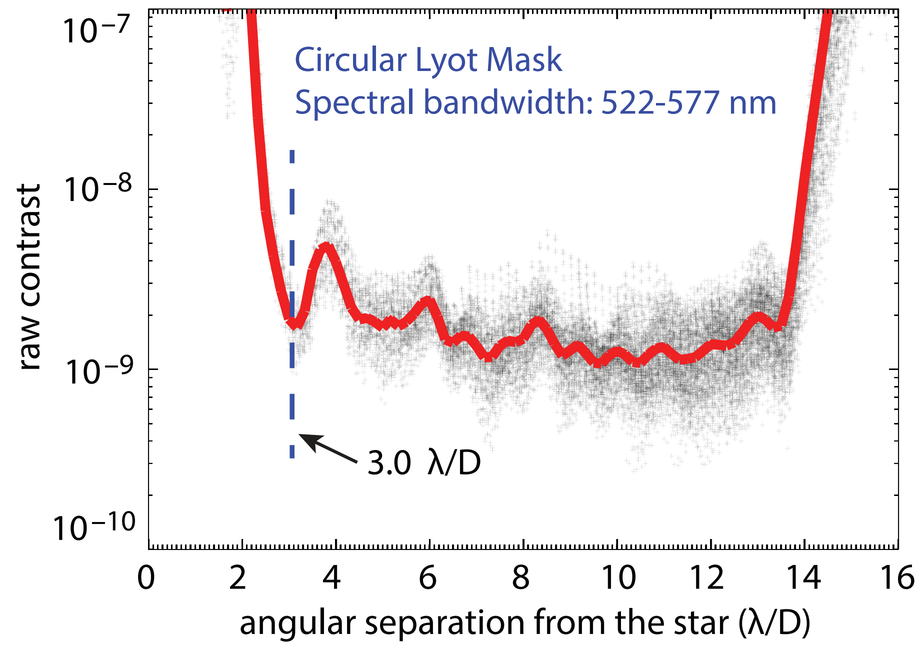
delta phase for DM1

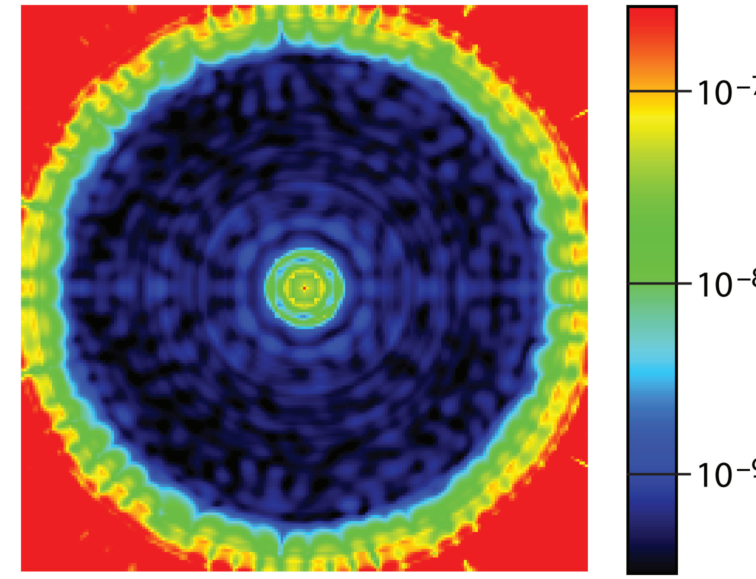


delta phase for DM2

AFTA coronagraph design

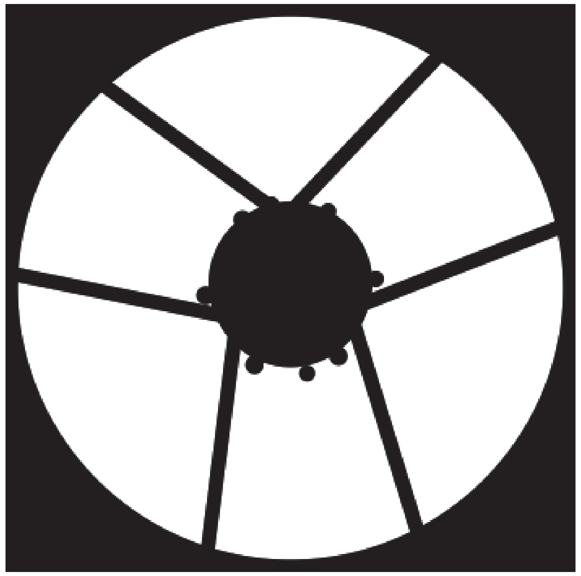


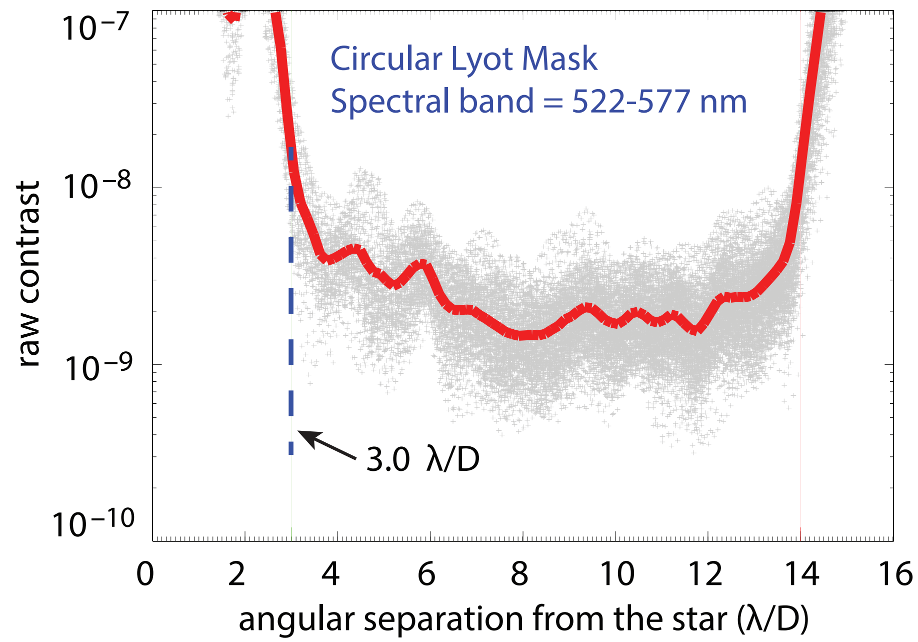


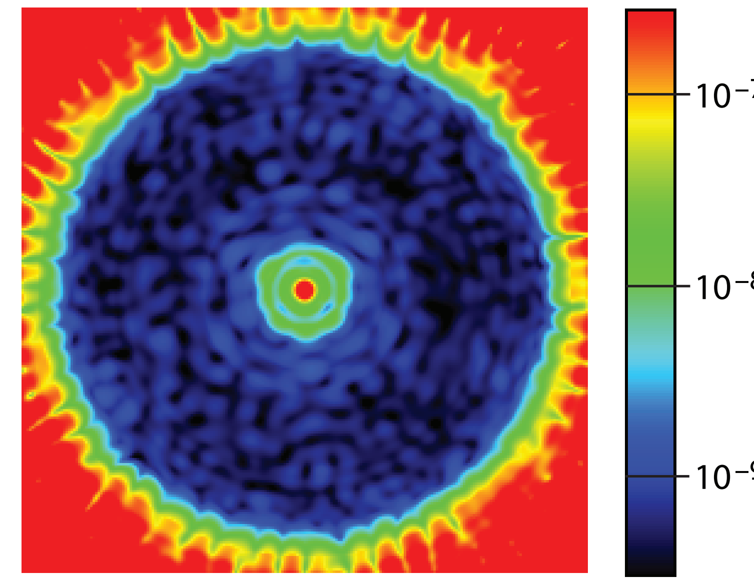


- *A **hybrid Lyot coronagraph** design is being optimized for a 2.4 meter telescope with central obscuration and six SM support struts*
- *Design utilizes a circular metal-dielectric Lyot focal plane mask plus Lyot stop and wavefront control with a pair of 48x48 actuator DMs*
- *Designed for **3.0 λ/D inner working angle and 10% spectral bandwidth**.*
- *Performance predictions are based on optical models that have been validated to the 2e-10 contrast level in TDEM/HCIT demonstrations (Trauger et al.).*

AFTA coronagraph design







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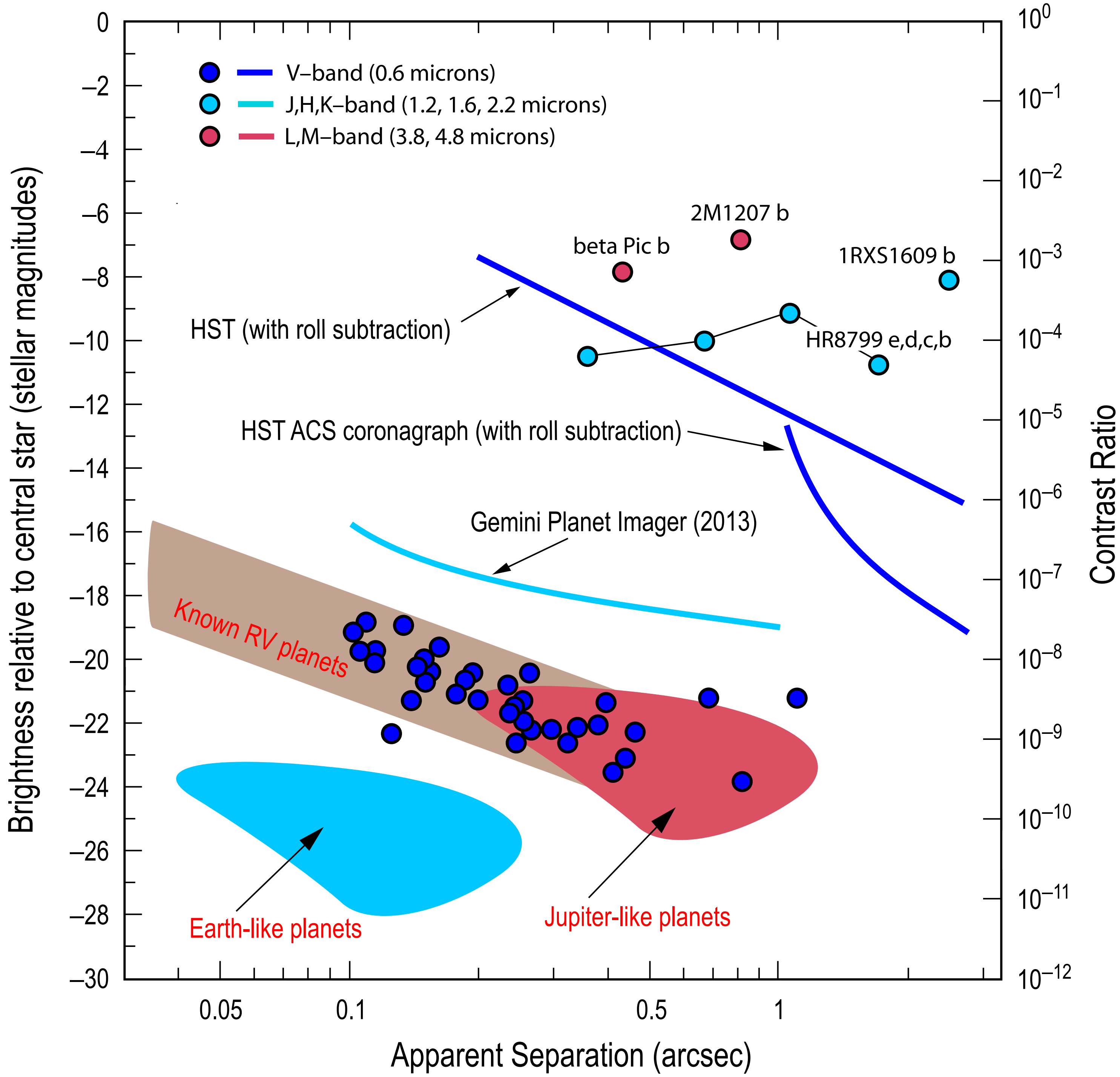
Status: hybrid Lyot coronagraph for the AFTA telescope

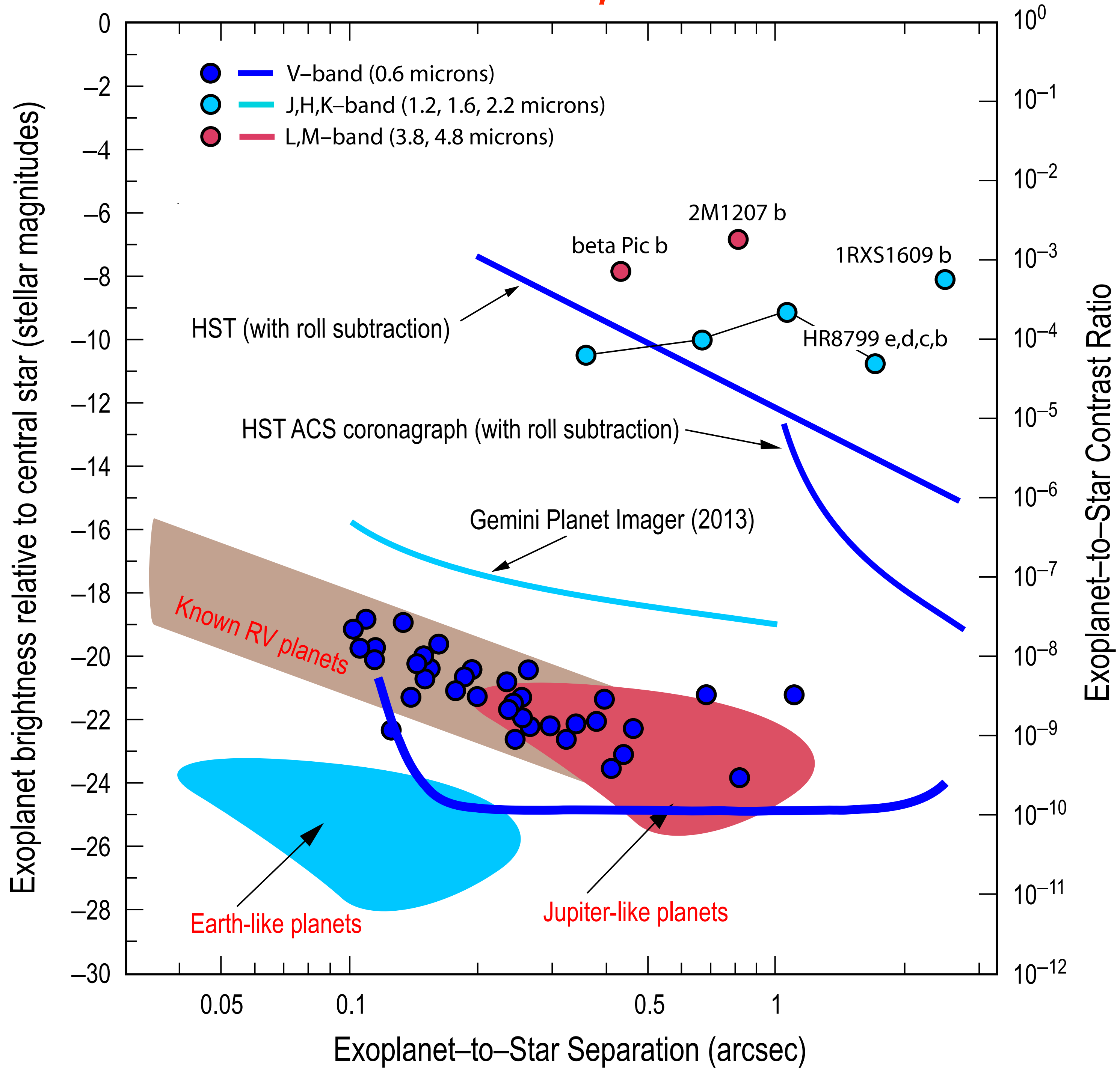
- *Hybrid Lyot design meets the AFTA MUST requirements (as currently understood).*
- *Technically, has low complexity, a robust technology for flight.*
- *Foregoing hybrid Lyot design is to be submitted to John Krist for detailed analysis and tolerancing.*
- *But further design optimizations are continuing – among the objectives:*
  - *Better contrast, especially at the IWA*
  - *Increased spectral bandwidth > 10%*
  - *Minimal DM peak-to-valley stroke*
  - *Increased throughput, optimal Lyot stop*
- *Fabrication of the mask is in progress under JPL institutional funding.*

Discovery space for direct imaging of exoplanets



- ***Blue dots:*** *36 exoplanets known from RV surveys with separations of 0.1 arcsec or more, as they would be seen at elongation in reflected starlight.*
- ***Light blue*** *and* ***red dots****: self-luminous exoplanets already imaged from the ground.*
- ***Red blob*** *is where Jupiter twins at 5 AU would be found, should they exist orbiting the nearest 100 FGK stars.*
- ***Blue blob*** *is for Earth twins at 1 AU.*

Exoplanet discovery space for the 2.4-meter obscured aperture telescope



- ***Blue coronagraph curve*** *illustrates the inner working angle (0.14 arcsec) and dark field contrast (1e-9 raw contrast, 1e-10 with post processing).*
- *Directly images the known RV planets with separations of 0.1 arcsec or more in reflected starlight.*
- *Sensitivity extends to super Earths and possibly a dozen Earth-like exoplanets.*
- *Facilitates color photometry and spectroscopy for atmospheric composition.*
- *Spectropolarimetry probes atmospheric cloud structure.*
- *Performance predictions derived from*
  - *New design studies for the obscured aperture coronagraph,*
  - *the ACCESS probe-class observatory concept study, and*
  - *TDEM coronagraph performance as demonstrated and validated in the laboratory.*

End