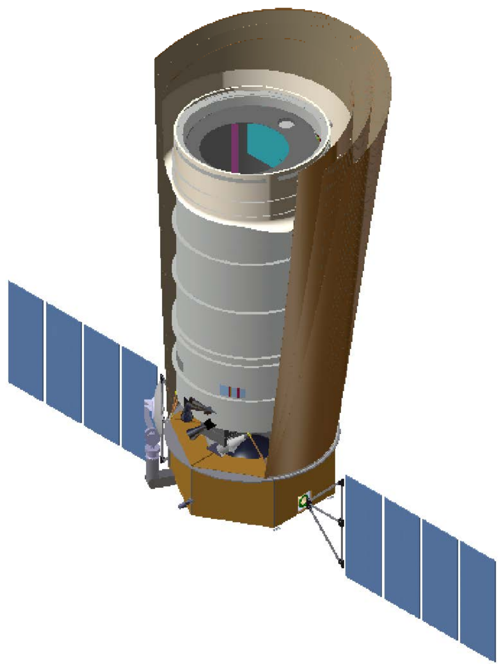
ACCESS -- a science and engineering assessment of space coronagraph concepts for the direct imaging and spectroscopy of exoplanetary systems



John Trauger (Jet Propulsion Laboratory / Caltech)

Exoplanet Exploration Program Workshop
Pasadena -- 22 April 2009

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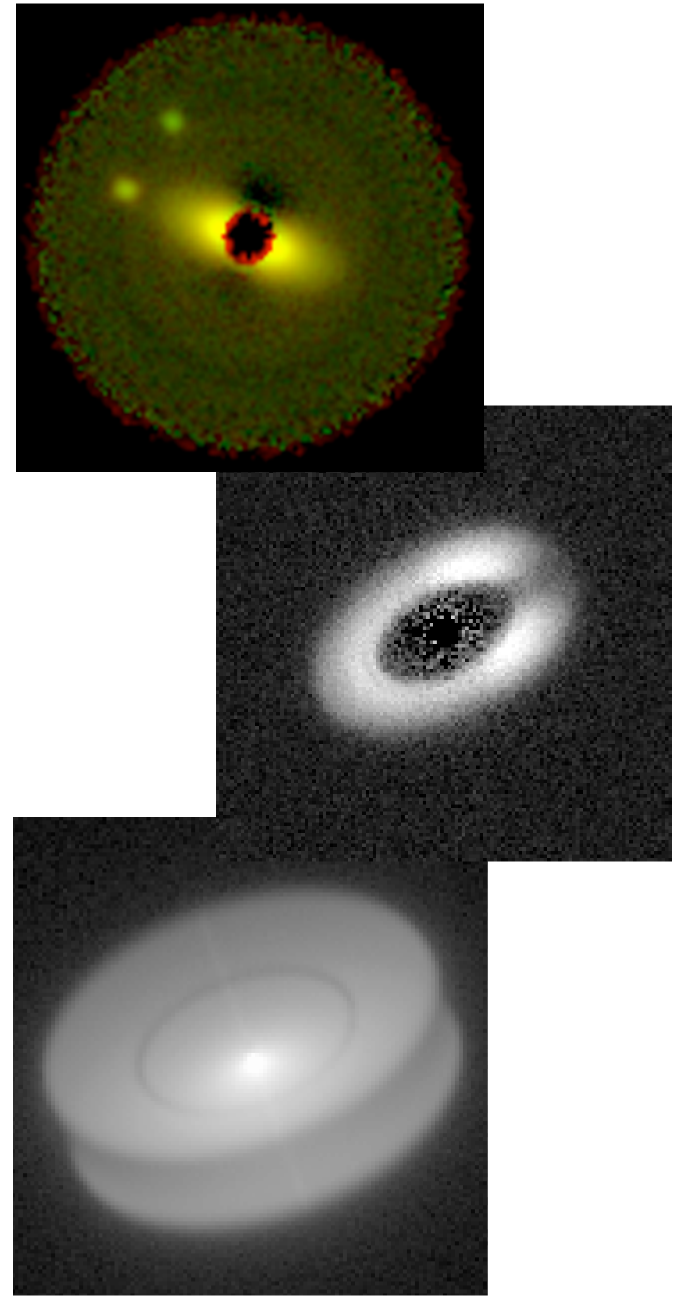
ACCESS = Actively-corrected Coronagraph Concepts for Exoplanetary System Studies

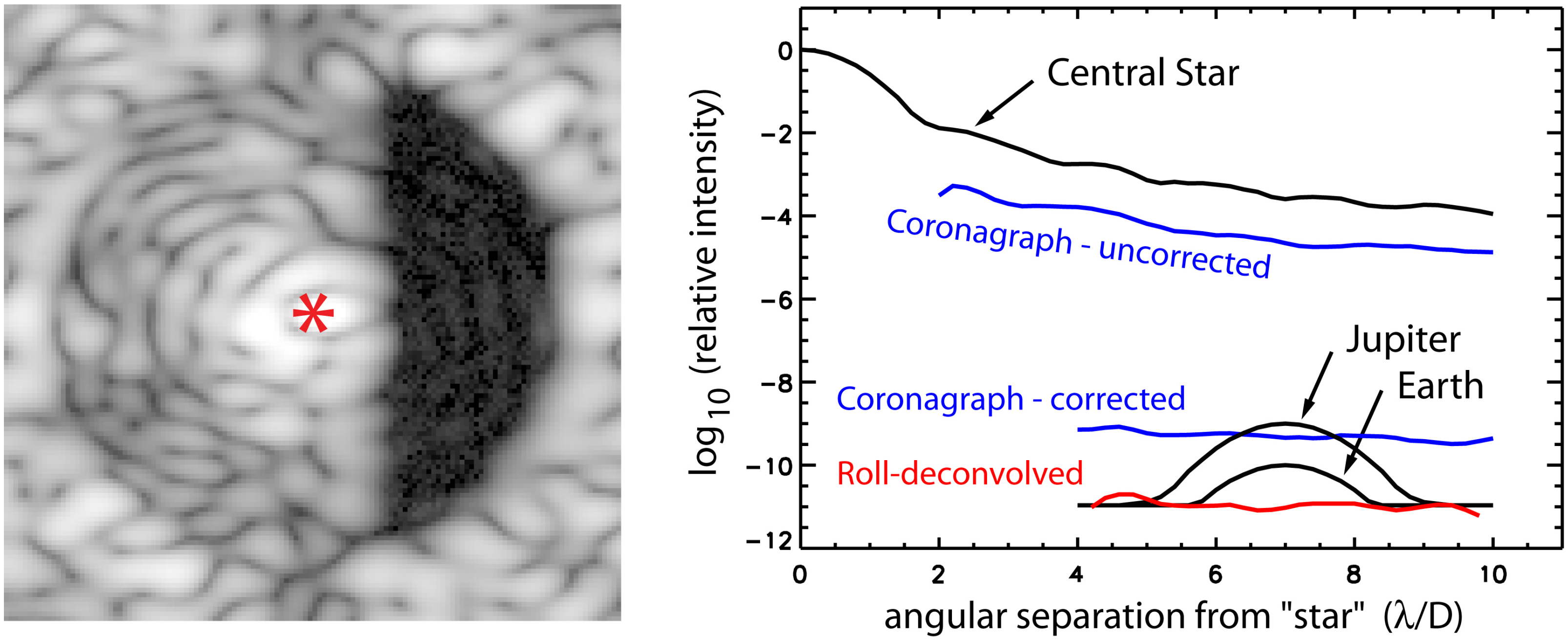
- *ACCESS is one of four medium-class exoplanet concepts selected by NASA for ASMCS studies ($660M + launch vehicle)*
- *Coronagraphic imaging and spectroscopy of exoplanetary systems in reflected starlight at visible wavelengths (450-900 nm)*
- *Study compares performance and readiness of four major coronagraph architectures*
- *Defines a conceptual space observatory platform as the "level playing field" for comparisons among coronagraph types*
- *Also uses laboratory validation on JPL's HCIT as another "level playing field" for coronagraph hardware readiness*
- *Evaluates science reach of a probe-class coronagraph mission*
- *Goal is to identify one or more capable mission concepts at TRL6+*

ACCESS science objectives

- Direct coronagraphic imaging and low-resolution (R=20)spectroscopy of exoplanet systems in reflected starlight, to include:
- Census of nearby known RV planets in orbits beyond ~1AU
- Search for mature exoplanet systems beyond the RV survey limits, including giant planets, super-earths, and possibly a dozen earth-mass planets
- Observe the life cycle of planetary systems: "dust-to-dust" in the circumstellar environment
- Observe Zodi structure as an indicator of unseen planets and planetesimals
- Survey Zodi dust as a critical architecture issue for future large life-finding exoplanet missions

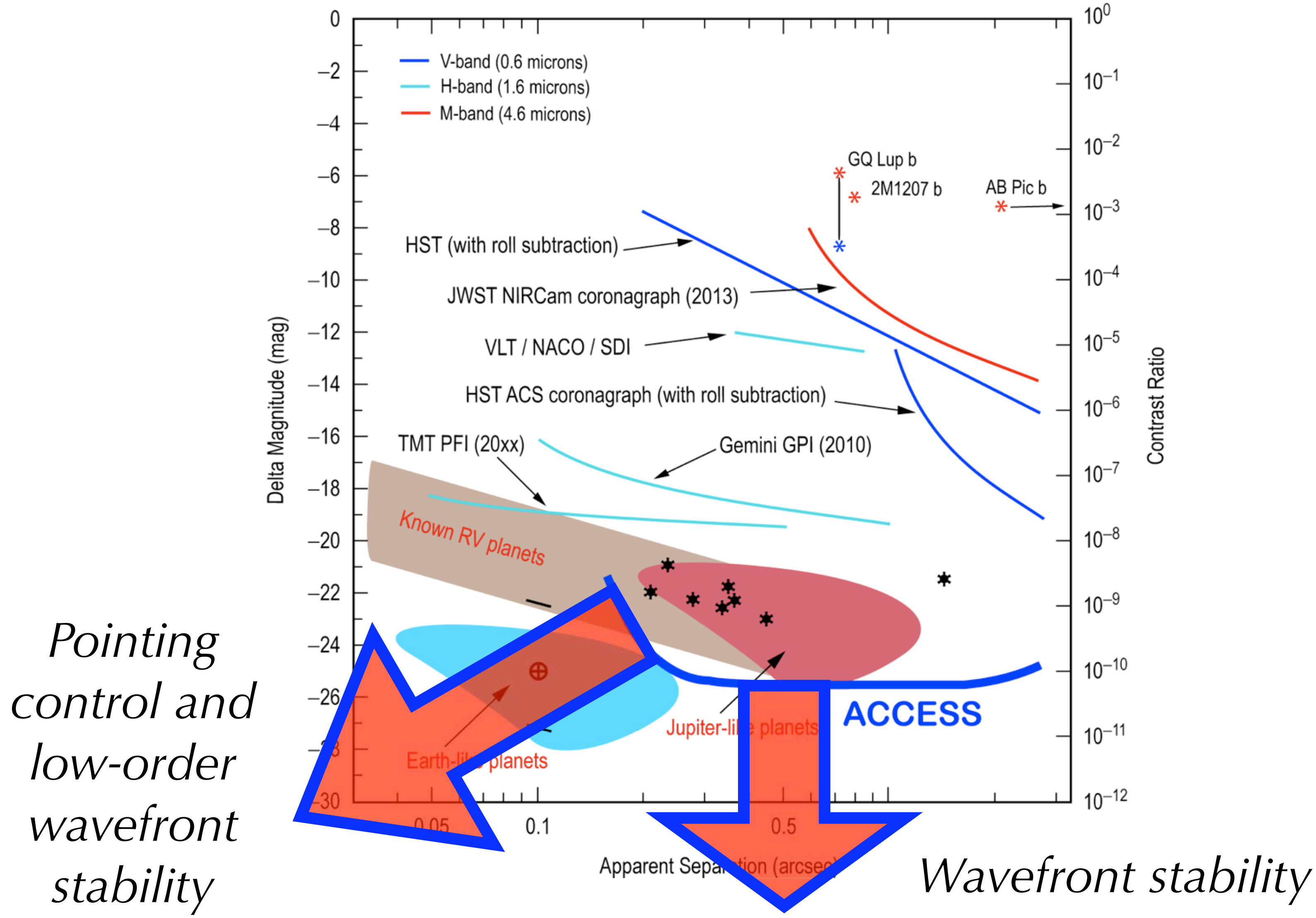


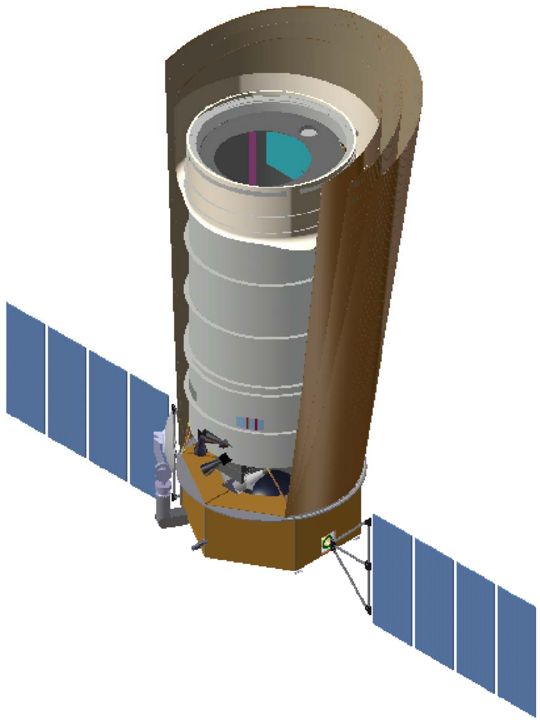
Laboratory coronagraph contrast and stability demonstrates capability to detect exoplanets



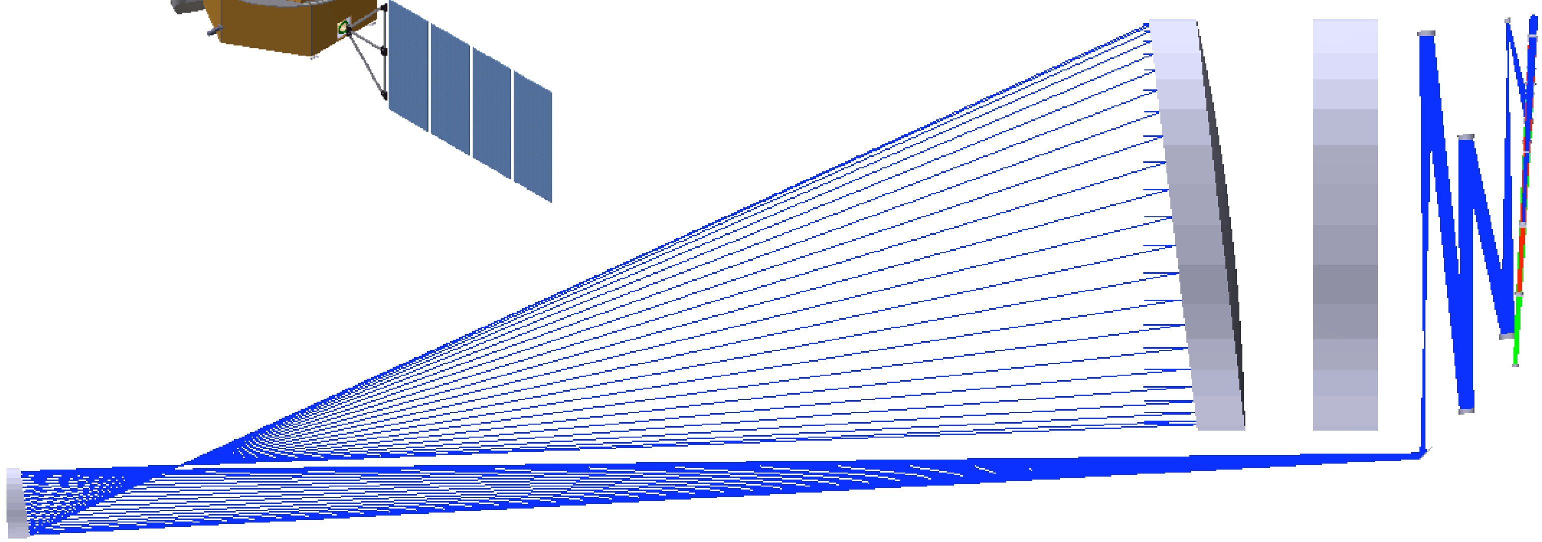
Comparison of azimuthally averaged PSFs of (a) the star, with focal plane mask offset and Lyot stop in place; (b) the coronagraph field with all DM actuators set to equal voltages; (c) the coronagraph with DM set for a dark half-field; and (d) the result of simulated roll deconvolution with the set of 480 consecutive coronagraph images. PSFs of a nominal Earth and Jupiter are also indicated. (Trauger & Traub, *Nature*, 12 April 2007, p771)

ACCESS Discovery Space is critically dependent on observatory pointing control and wavefront stability





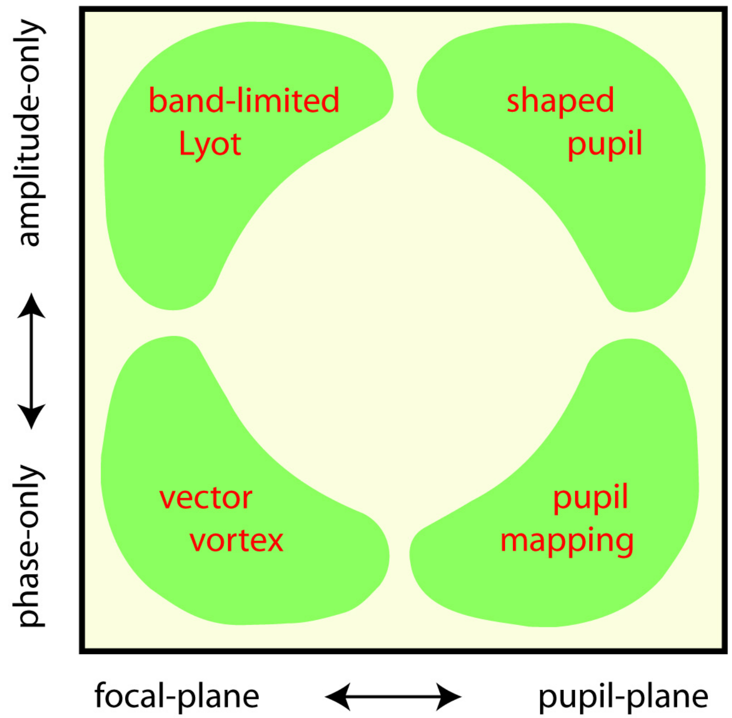
ACCESS observatory:
1.5 meter -
unobscured off-axis
gregorian telescope

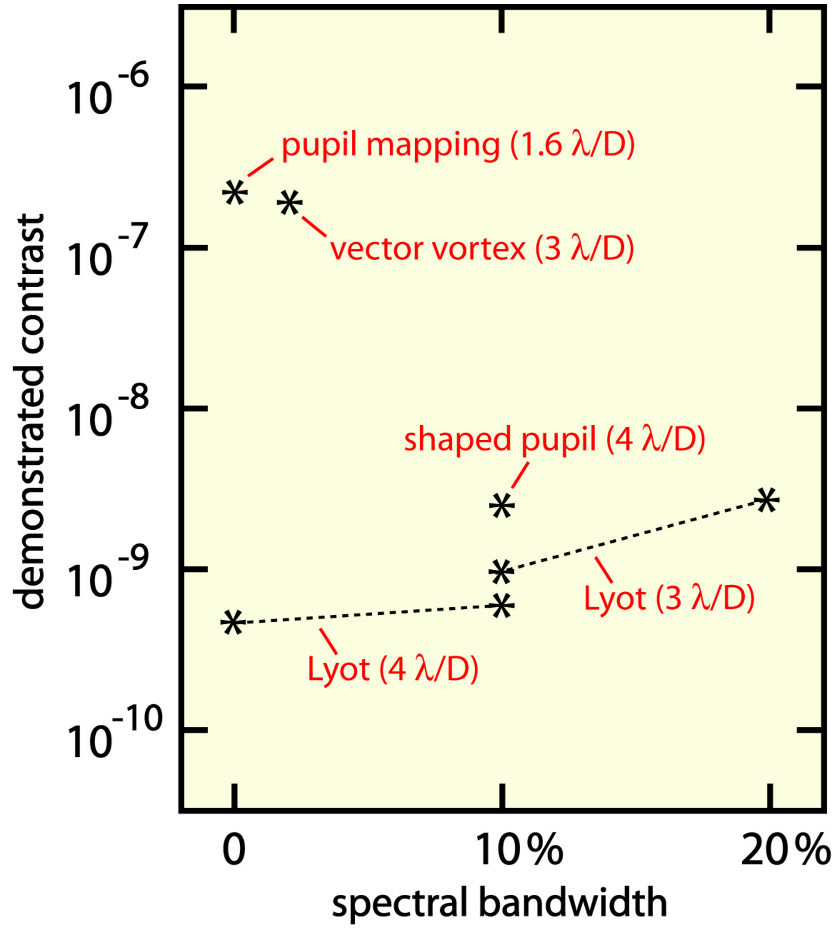


ACCESS observatory

- *Observatory architecture is representative of the "best" available for exoplanet coronagraphy within the scope (cost, risk, schedule) of a NASA medium-class mission*
  - *visible wavelengths (500-900 nm) for smaller λ/D and better IWA*
  - *single spacecraft (external occulter + telescope exceeds medium cost)*
- *In particular, all coronagraphs require an observatory system with*
  - *exceptional pointing control*
  - *exceptional wavefront stability and*
  - *active (deformable mirrors) wavefront control*
- *ACCESS requires systems with high technology readiness (TRL6+) for*
  - *reliable estimates of science capabilities and*
  - *reliable determinations of cost and schedule*
- *Baseline observatory architecture defines a capable platform for meaningful comparisons among coronagraph types.*

ACCESS gamut of coronagraph types

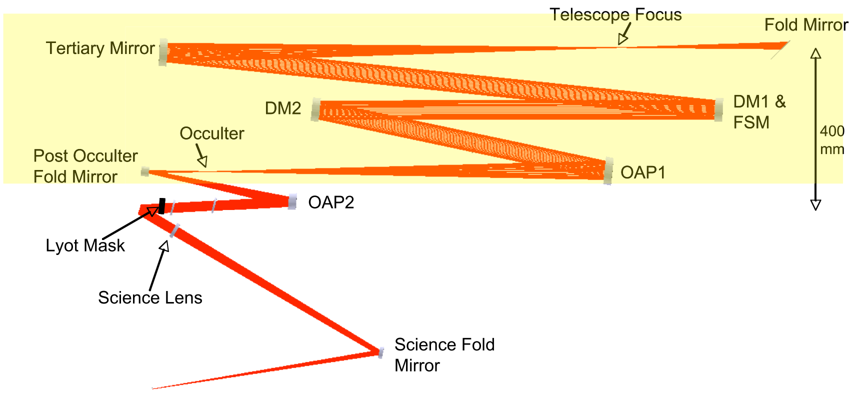




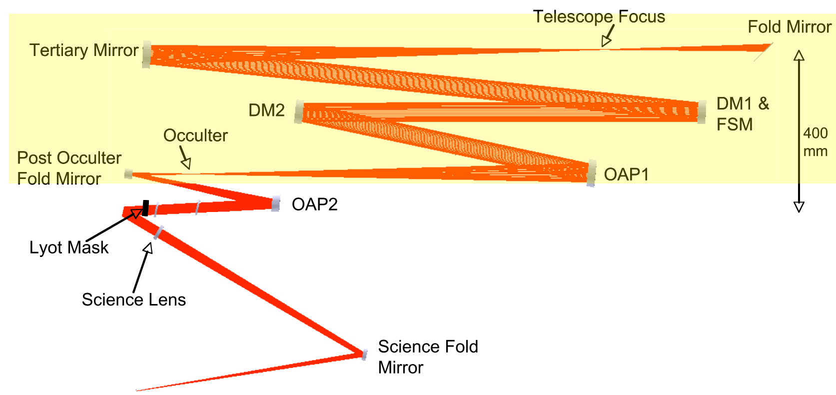
The four major coronagraph types perform starlight rejection with combinations of phase and amplitude elements placed in focal and pupil planes. Best demonstrated laboratory contrast to date (March 2009) are indicated at right, while noting that significant improvements are expected this year as an outcome of active laboratory developments with well-understood technologies.

ACCESS compares four major coronagraph types

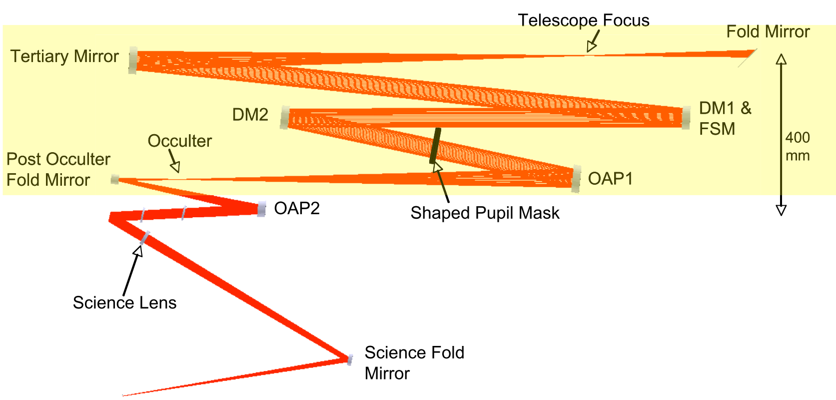
Lyot coronagraph



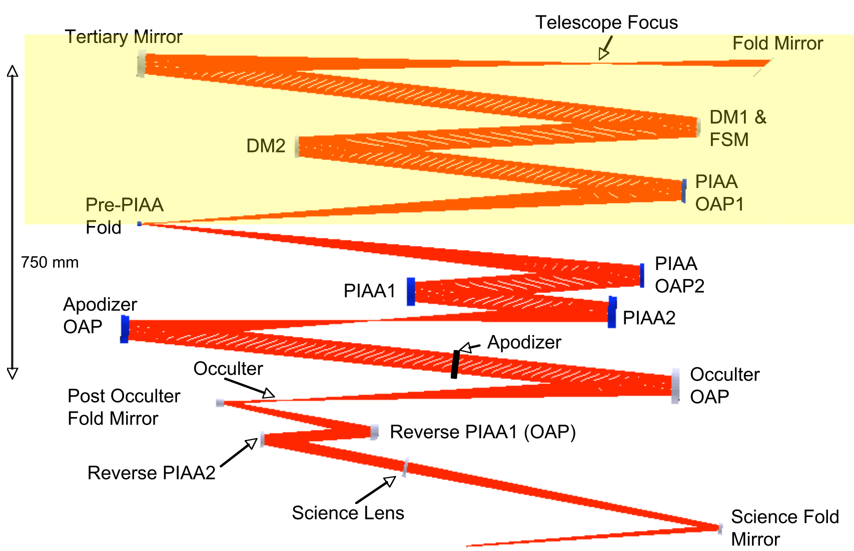
Vortex coronagraph



Shaped pupil coronagraph

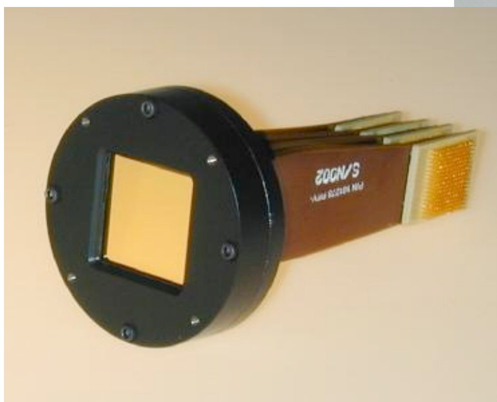


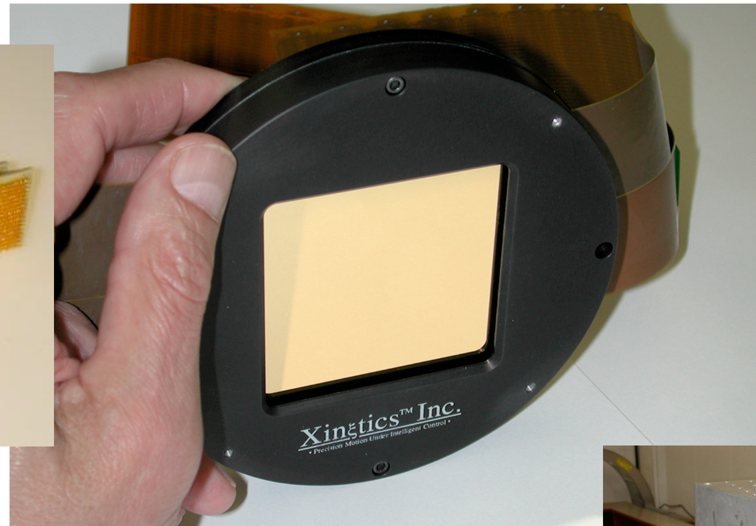
Pupil mapping coronagraph

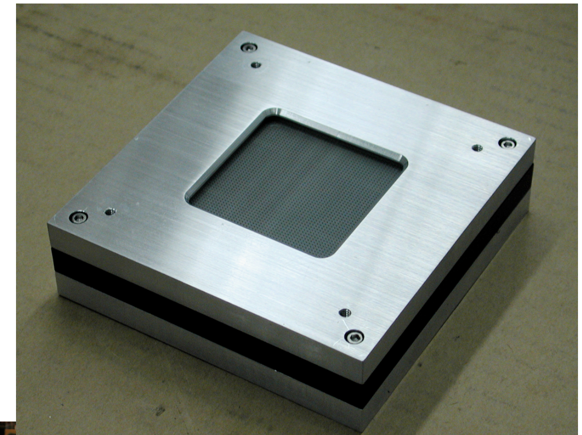


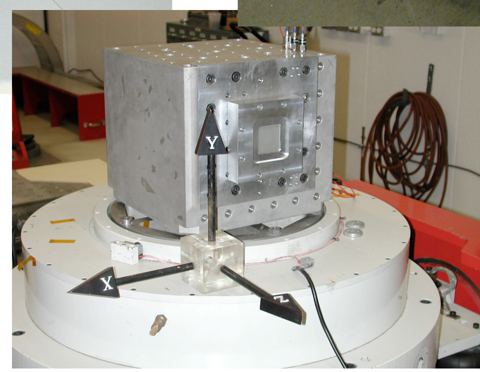
(Note: highlighted elements, including FSM, DMs, and pointing control system, are common to ALL four coronagraph types)

Precision deformable mirrors provide wavefront control





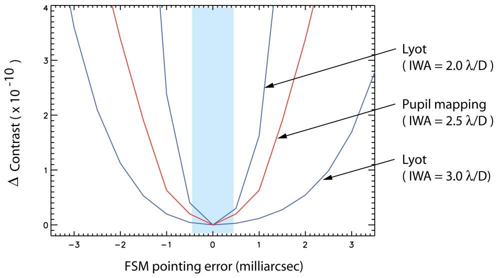




Evolution of monolithic PMN deformable mirrors: left to right: 32x32 array, used for all HCIT milestones to date; 64x64 array to be installed on HCIT spring 2009; 48x48 array (also shown on JPL shake table) will be used to demonstrate TRL6 flight-readiness this year.

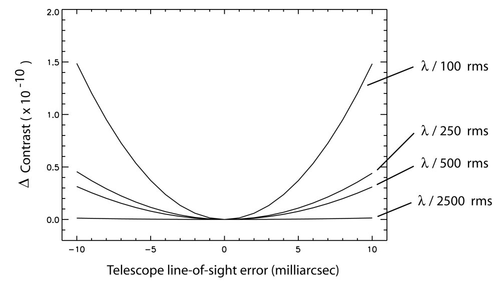
Mirror facesheets are fused silica, with surfaces polished nominally to λ/100 *rms. Surface figure (open loop) is settable and stable to 0.01 nm rms over periods of 6 hours or more in a vacuum testbed environment. All DMs were delivered to JPL by Xinetics.*

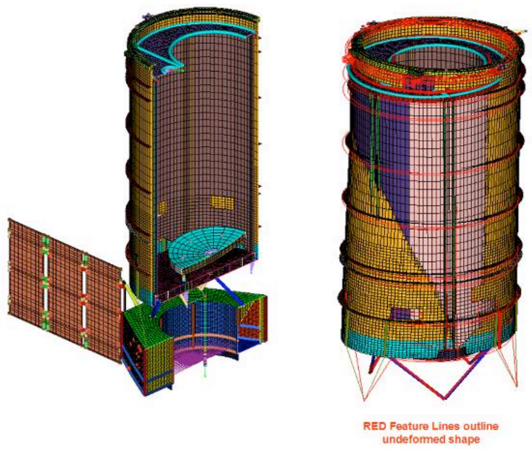
Observatory pointing and thermal control systems



Fine steering mirror stabilizes the star image on the coronagraph occulting mask (all four coronagraphs have an occulting mask) to 0.45 milliarcsec (3-sigma), as required for high contrast at inner working angles as small as 2 λ/D. Contrast deltas at the IWA for representative coronagraphs designed for 2.0, 2.5, and 3.0 λ/D are shown for illustration.

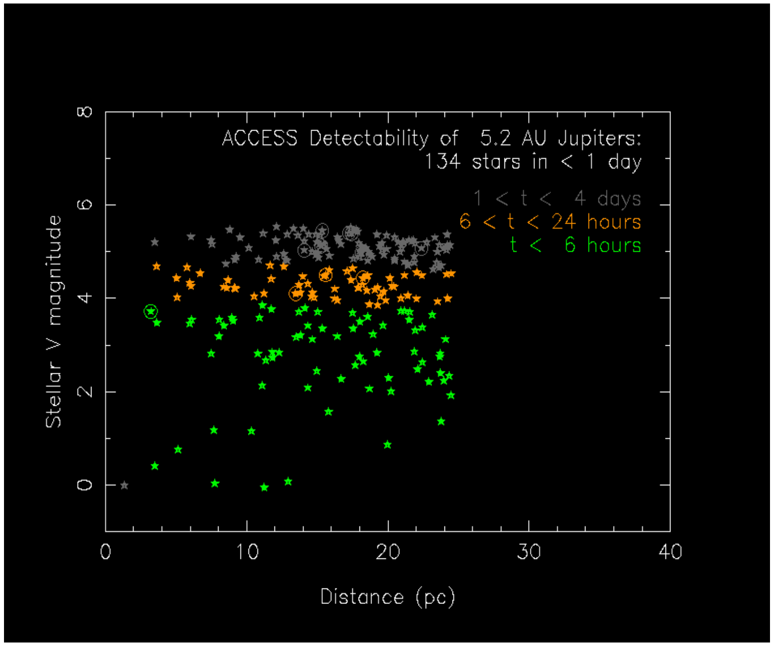
Telescope body pointing (i.e., line of sight) is stabilized to 1 milliarcsec (3 sigma) with an active jitter control system. Shown here are the contrast deltas (vs. rms surface figure of the optical elements following the primary mirror) due to beamwalk on the optics upstream of the fine steering mirror.

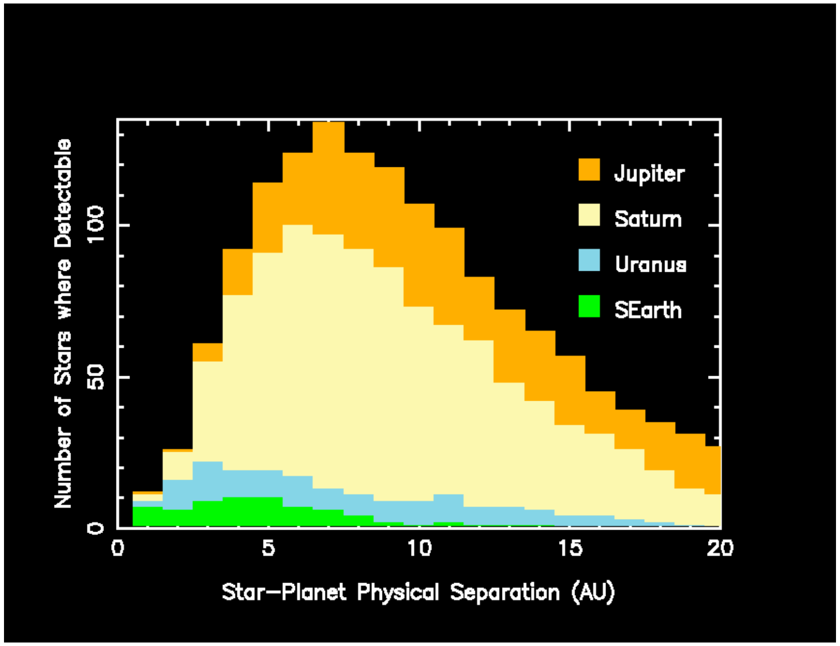




Structural and thermal models guide the observatory design and inform the optical performance models with estimates of structure dynamics, vibration isolation, pointing control, thermal gradients across the primary mirror and forward metering structures, alignment drift in response to telescope slews and roll.

Exoplanet search space





Examples of exoplanet search space. At left, a plot of integration times needed to detect Jupiter twins within 45 degrees of elongation from their parent stars, to S/N = 10, using the ACCESS Lyot coronagraph with an IWA = 2 lambda/D. At right, the number of planets detectable to S/N = 10, in integration times of 1 day or less, using the ACCESS Lyot coronagraph with an IWA = 2.5 lambda/D.

Science completeness metric: 2.0, 2.5, and 3.0 λ/D

Table 1: Number of nearby stars that can be surveyed for 5.2 AU Jupiters, IWA 3.0 λ/D

Coronagraph Type	Planet 45° from max elong	Planet 15° from max elong
Lyot	117	175
PIAA	166	278
Vortex	135	204

Table 2: Number of nearby stars that can be surveyed for 5.2 AU Jupiters, IWA 2.5 λ/D

Coronagraph Type	Planet 45° from max elong	Planet 15° from max elong
Lyot	153	218
PIAA	178	267
Vortex	154	228

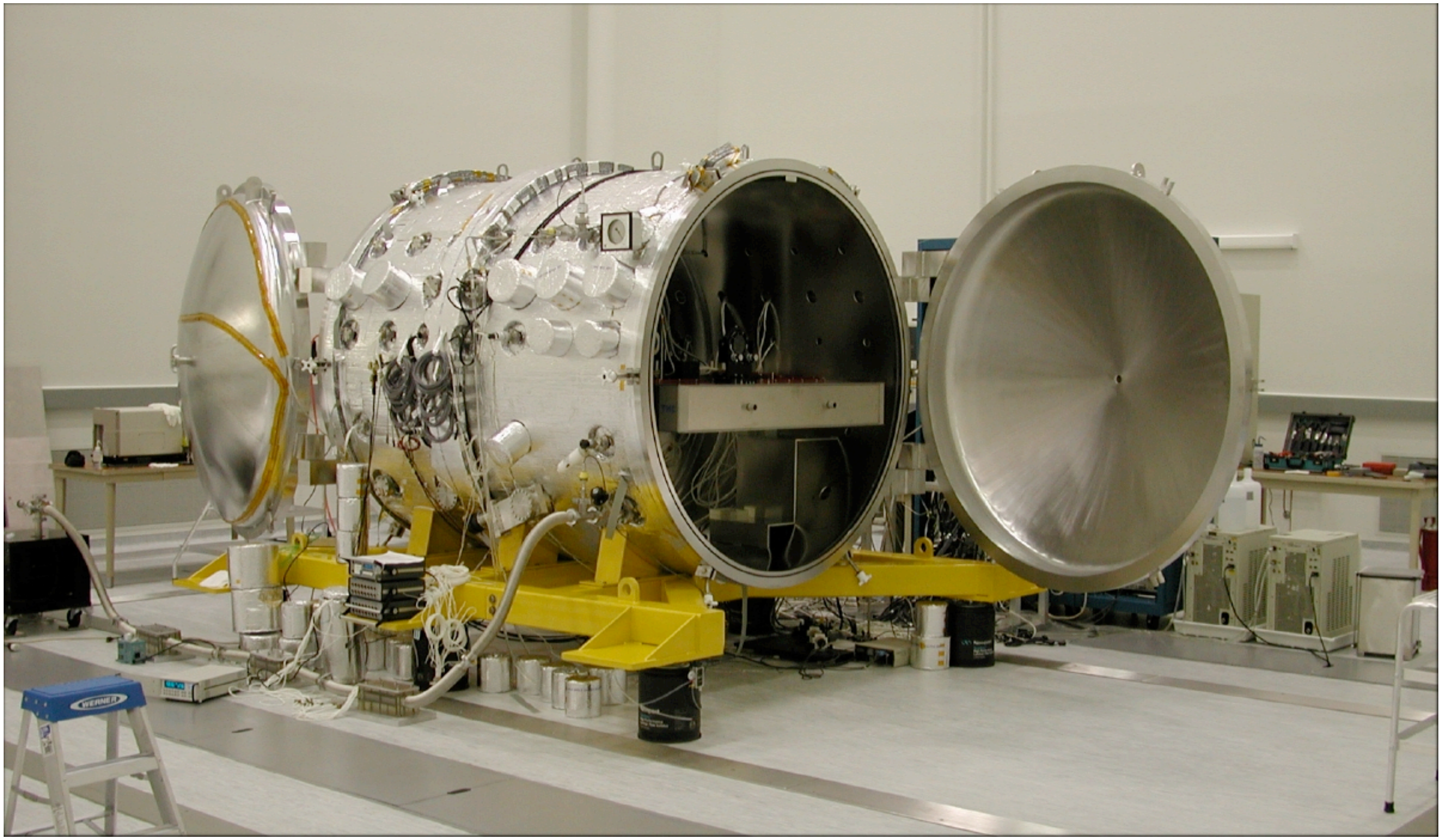
Table 3: Number of nearby stars that can be surveyed for 5.2 AU Jupiters, IWA 2.0 λ/D

Coronagraph Type	Planet 45° from max elong	Planet 15° from max elong
Lyot	170	230
Vortex	164	241

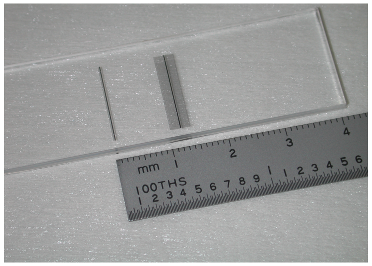
Note: Accurate PIAA wavefront control solution not available for this IWA

Tabulation of the number of nearby AFGK stars that could be searched with various ACCESS coronagraphs to the depth of 10-sigma detections of Jupiter twins in each of six visits to the star over a period of 2.5 years. Columns for 45 degrees from maximum elongation corresponds to an observational completeness of 50% or more in each visit, approaching 100% after six epochs spread over several years, and for systems with more than one major planet.

All four coronagraph types are to be tested in JPL's High Contrast Imaging Testbed

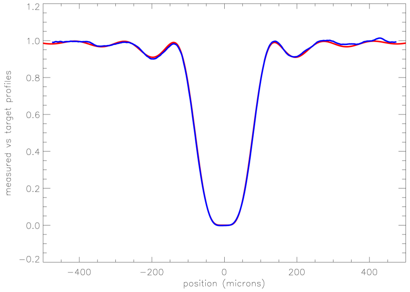


Lyot coronagraph demonstrations on the HCIT



THICKNESS-PROFILED NICKEL MASK

Nickel mask has been vacuum-deposited on a fused silica substrate. Attenuation profile was built up in a number of passes with a computer-controlled moving slit. The same mechanism will be used to superimpose a dielectric phase layer in future work.

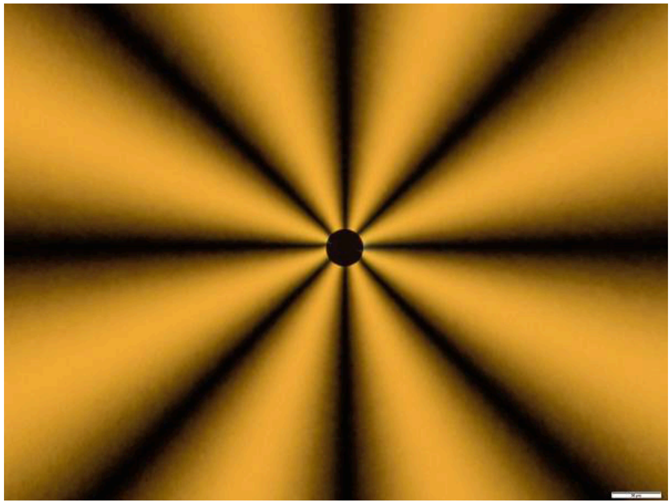


Comparison of the prescribed transmittance profile with the measured profile of the mask pictured at left. Desired profile is the red curve, the measured profile is the blue curve.

Recent contrast demonstrations in the HCIT:
IWA = 3 λ/D, 10% bandwidth, C = 1.2 e-9
IWA = 3 λ/D, 20% BW, C = 2.7 e-9
IWA = 4 λ/D, 10% BW, C = 6 e-10,
with 4th-order metallic or metal+dielectric 4th-order Lyot masks. All masks manufactured at JPL. Narrower (2.5 λ/D) Lyot masks, and circular masks will be manufactured this year.

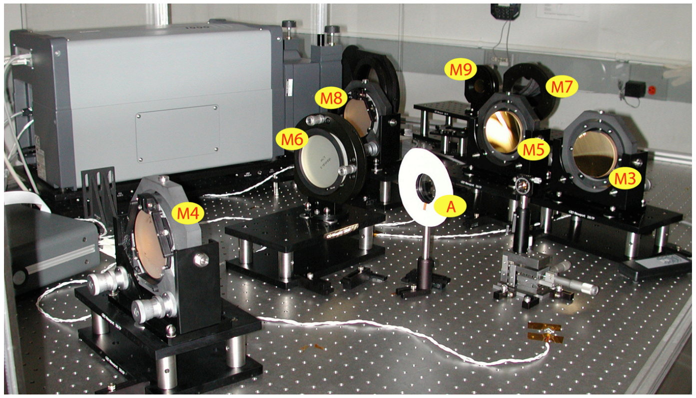
Vector vortex coronagraph mask for HCIT experiments

Recent contrast demonstrations in the HCIT:
IWA = 3 λ/D, 2% bandwidth, C = 2.0 e-7
with the first-ever charge-4 liquid crystal polymer vortex mask from JDSU (seen at left through crossed polarizers). Close agreement between HCIT performance and models predict that reduction of internal reflections and multilayer achromatization will lead to contrast ~1e-9 with a 20% bandwidth, to be attempted by the end of this year.

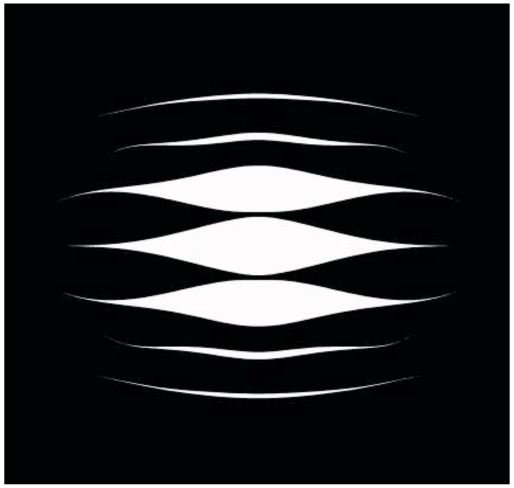


HCIT laboratory setup for pupil mapping demonstrations

To date, the best contrast result for a pupil mapping (PIAA) coronagraph:
IWA = 1.6 λ/D, monochromatic, C = 2.2e-7
was achieved by Guyon (2009) at the Subaru Observatory laboratories. A new PIAA system, commissioned by NASA/Ames and manufactured by Tinsley, is now mounted in the HCIT in preparation for its first experiments in a vacuum environment.



Shaped pupil coronagraph experiments with HCIT



At left, the transmittance profile of a representative shaped pupil apodization (black indicates opaque). This "Ripple 3" design achieved:
IWA = 4 λ/D, 10% bandwidth, C = 2.4 e-9
on the HCIT (Belikov et al. 2007). Smaller inner working angles are possible with the use of a pair of DMs

Summary

- *The ACCESS study considers the relative merits and readiness of four major coronagraph types, and hybrid combinations.*
- *Using demonstrated high-TRL technologies, the ACCESS minimum science program surveys the nearest 100+ AFGK stars for evidence of planetary systems.*
- *Follow-up with R=20 spectrophotometry.*
- *Technology demonstrations in the coming year are expected to further enhance the science reach of an ACCESS mission, in advance of a NASA AO for a medium class mission.*
- *The study also identifies areas of technology development that would advance the readiness of the major coronagraph types in the coming 5 years.*

End