



Exoplanet Exploration Coronagraph & Occulter Technology Infrastructure at JPL

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High Contrast Imaging Testbed - HCIT



Facility

- Vacuum Chamber – L = 7.5'; ϕ = 6'; P = 1 mTorr
Seismically isolated, T-stabilized \sim 10 mK @ room temp.
- Achieved 3×10^{-10} contrast (narrowband)
- Wavefront control with 32x32mm Xinetics Deformable Mirrors w/ 1mm pitch. 64x64mm soon.
- Fiber/Pinhole "Star" Illumination
 - Monochromatic: 635, 785, 809 and 835 nm
 - 2, 10 and 20% BW around 800 nm center
 - Medium and High Power Supercontinuum Sources
- Low-Noise ($5e^-$) CCD camera, 13 μ m pixels
- Complete computer control w/ data acquisition & storage
- Safe & convenient optical table installation/removal
- Parallel in-air preparation & modifications to coronagraphs
- Remote access through FTP site

Test Capabilities

- LYOT Coronagraph configuration – Table #1
 - Band-Limited Occulting Masks
 - Shaped-Pupil Masks
 - Vector-Vortex Masks
- Phase-Induced-Amplitude-Apodization (PIAA) Coronagraph – Table #2
- Narrow or broad band coronagraph system demos
- Investigation of novel system configurations (e.g., DM placement)
- Coronagraph model validation & error budget sensitivities



HCIT with Lyot Coronagraph Installed



HCIT with Lyot Coronagraph Installed

Wavefront Sensing & Control



Nulling Algorithms

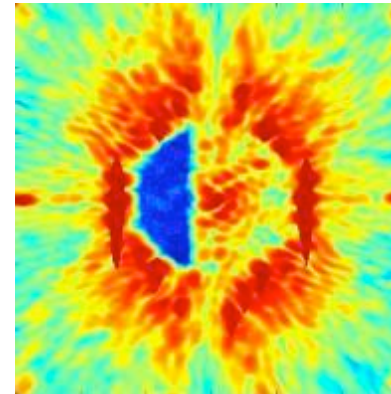
- Electric Field Conjugations (EFC) algorithms exist for single and dual DM control
- Demonstrated to $< 10^{-9}$ contrast and 20% BW
- Applicable for Lyot, Shaped Pupil, Vortex & PIAA
- Coupled to HCIT coronagraph models and DM calibration data for optimal efficiency

Deformable Mirrors

- Xinetics DMs available for single and 2 DM tests:
 - 32x32mm (3) & 64x64mm (1)
 - 48x48mm available in 2010
 - Fuse Silica facesheet polished to $\lambda/100$ rms
 - Surface stable to 0.01 nm rms over > 6 hours in vacuum

Test Capability

- Proposed experiments can capitalize on existing WFS&C capabilities to complement starlight suppression demonstrations
 - New coronagraph demonstrations w/ existing S/W & DM
 - New algorithm demonstration w/ existing DMs
 - New DM demonstrations on existing coronagraph
 - Proposer to provide DM electronics, calibration data and any new H/W for HCIT optical configuration
 - Apply EFC to novel coronagraph models to determine by analysis if there are any limitations to broadband contrast and to look for advantages/disadvantages of the coronagraph in terms of WFS/C.



EFC Nulling and current performance

Best Results to Date
Band-Limited Coronagraph :
 6e-10, @ 4 λ/D with 10% light
 1.2e-9, @ 3 λ/D with 10% light
 2.7e-9, @ 3 λ/D with 20% light

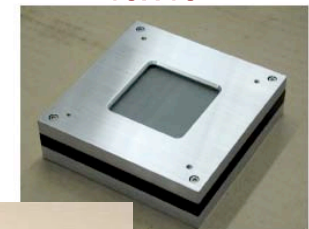
Shaped-Pupil Coronagraph:
 1.16e-9, @ 4 λ/D with 2% light
 2.4e-9, @ 4 λ/D with 10% light

Vector Vortex Coronagraph:
 2e-7, @ 3 λ/D with 2% light

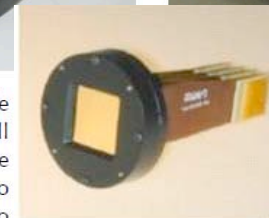
Xinetics Deformable Mirrors

64x64

48x48



PMN deformable array, used for all 64x64 array to be 48x48 array (also e) will be used to



32x32

Xinetics DM

Coronagraph Modeling & Error Budgets



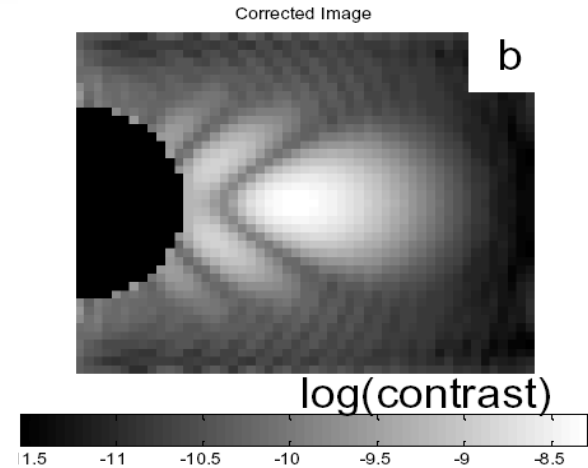
Coronagraph Modeling

- Multiple models and tools are available:
 - Optical diffraction tools with Fresnel propagation and active wavefront control for simulations of broadband contrast performance
 - Includes mask transmission errors, alignment & optical figure errors, nulling algorithms w/ deformable mirror influence functions
 - Lyot and PIAA propagation models are available
 - HCIT Testbed models for Lyot and PIAA
 - Mission simulation, orbit determination, spectra characterization

Generalized Error Budget Tool

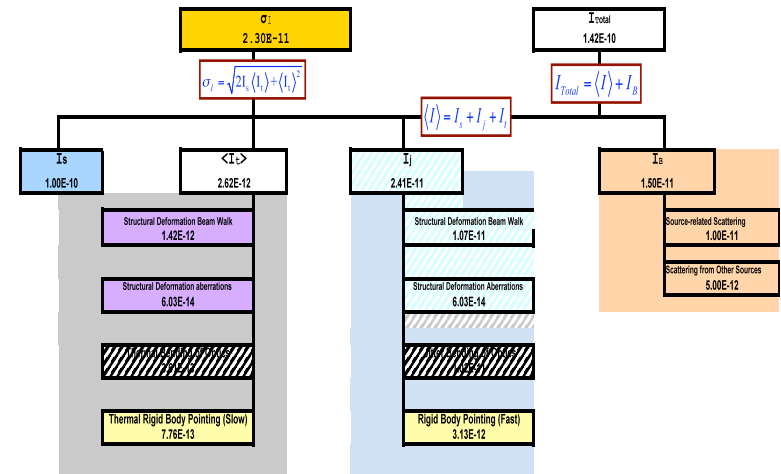
- Automated error budget tool for any internal coronagraph system:
 - observatory tolerances to back-end contrast
- Based on diffraction analyses of specific coronagraphs (Lyot, PIAA, Vortex) & sensitivities of actual optical prescriptions
- Near-seamless integration of Matlab-code and Excel macros for rapid prototyping
- Specifying Milestone performance goals tied to flight missions
- Defining testbed error budgets and sensitivities for model validation

TDEM application



PIAA residual image after DM correction (Shaklan SPIE 2007)

Coronagraph Error Tree:



Coronagraph Error Budget Tool Screenshot

Integrated Modeling Tool: CIELO

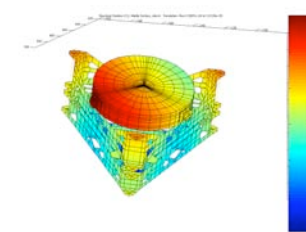
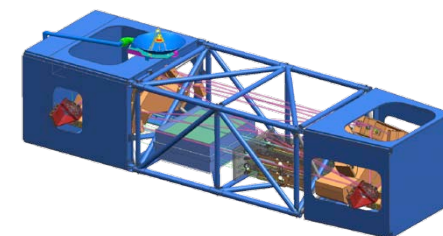
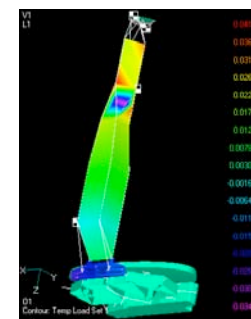
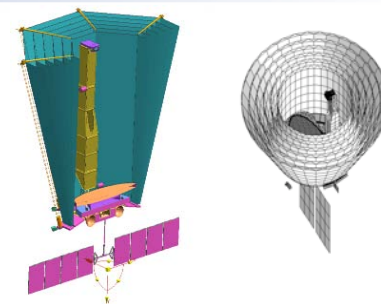


General-purpose finite element computational tool for multi-physics analysis:

Thermal – Structures – Optics - Control

ExoPlanet Exploration Program

- Unique Attributes:
 - Provides integrated common thermal & structural model w/ subsequent optical aberrations :
 - no “bucket brigade” or mesh interpolation
 - Matlab hosted and Nastran input file driven
 - Runs on serial and parallel machines
 - Eliminates model size limits of COTS thermal codes
- Advantages:
 - Turnaround time improved via common model
 - Wall clock time improved via parallel computing
 - Accuracy improved w/ finer mesh & double precision
- Unique analysis capabilities
 - Parametric multi-physics sensitivity analysis for performance optimization, uncertainty quantification, error budget tolerancing & verification
 - Multi-physic test/model correlation
 - Integration w/ other domain (eg controls)



External Occulter Modeling



ExoPlanet Exploration Program

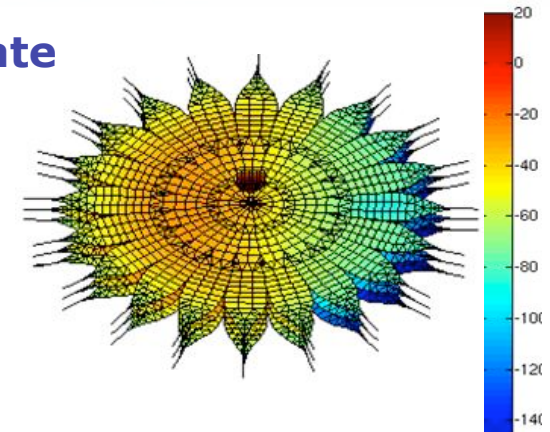
- **Large scale optical diffraction models to simulate the effect of petal deformations and imperfections on contrast**

- Models built for representative design and validated against THEIA results
- Efficient algorithm can handle large problems

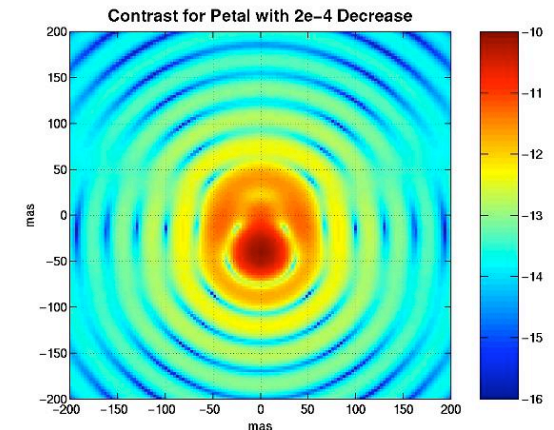
- **Thermo-mechanical finite element models using in-house integrated analysis code CIELO**

- Single model for thermal & structures w/ high fidelity at petals edges – no extrapolation
- Perform transient slew & settle thermal deformation analysis
- Investigate damping and nonlinear joint dynamics
- Perform parametric sensitivity analyses to material property distributions, for performance optimization...
- Validate models against sub-scale test articles

- **Seamless hand-off of structural deformation data to optical contrast analysis.**



Thermal model (°C) of 3-layer flat external occulter w/ Sun at 5°



Contrast degradation due to 1mm width change in a single petal (20 petals, 54m tip-tip occulter)

Technology for Coronagraph Masks



Fab Capability for Various Mask Types

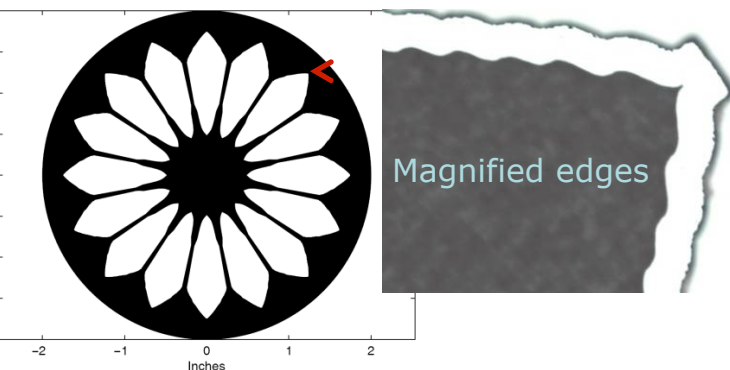
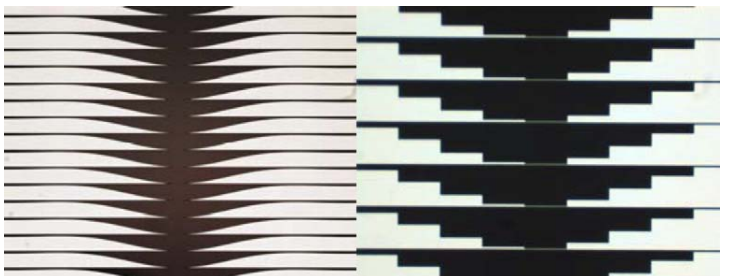
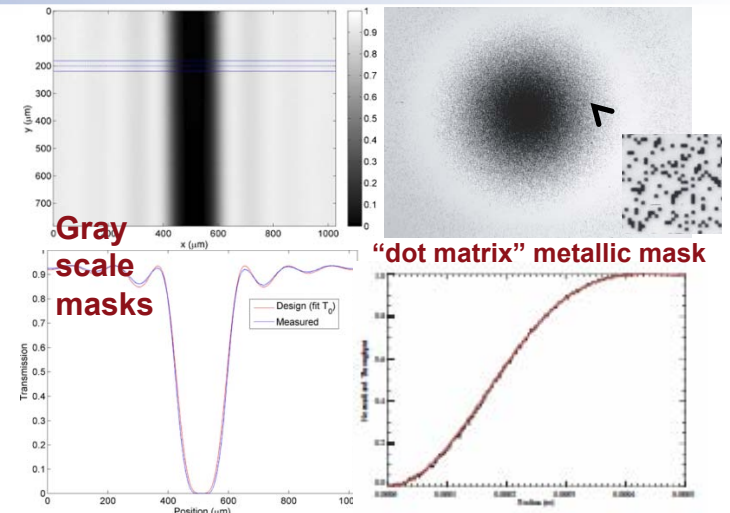
Electron Beam Lithography, Deep Reactive Ion Etching, sub micron dimensions

- Focal plane LYOT Coronagraph masks – model-based design
 - Gray scale HEBS masks (JPL)
 - Binary metallic masks (JPL)
 - Gray scale metallic masks for broadband (JPL)
 - Material selection, layers and structure optimization for broadband OD and phase performance (JPL)
 - “dot matrix” metallic masks (JWST NIRCcam, JPL)
 - Vector vortex masks (JPL, JDSU)
 - PIAA Occulting Masks, post-apodizer (JPL, Ames, UA, Princeton)

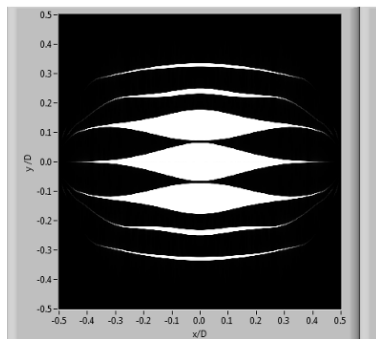
- Free standing shaped pupil masks (JPL, Princeton)
- Free standing lab-scale external occulter masks (JPL, Princeton)

Characterization Capabilities

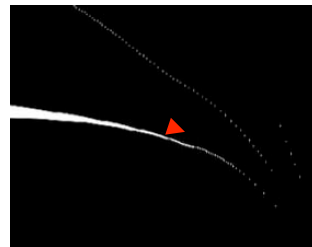
- Precision spectro-photometry
- Scanning optical & electron microscopy
- Defect mapping & scatter analysis
- Model validation



ExoPlanet Exploration Program



Free standing shaped pupil mask



TDEM plotting

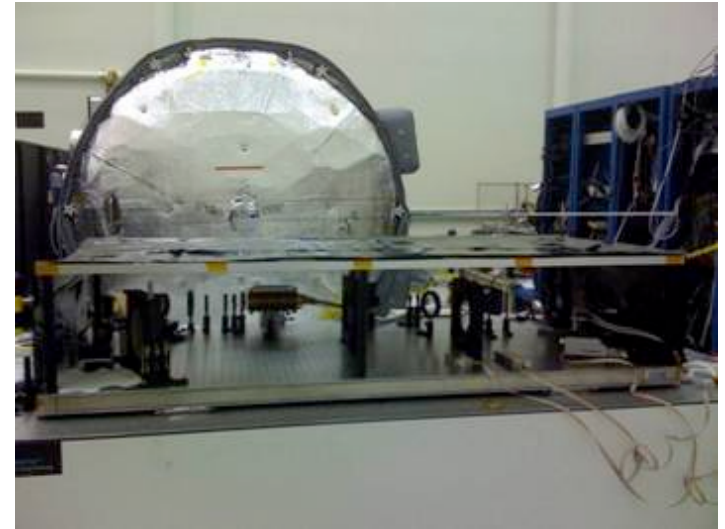
Free standing lab scale external occulter

Vacuum Surface Gauge for Accurate Wavefront Measurement and Deformable Mirror Calibration

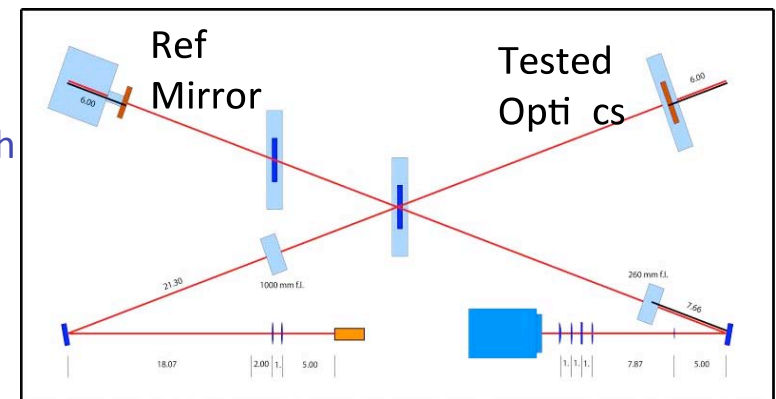


ExoPlanet Exploration Program

- Customized Michelson Interferometer set-up
 - Reference mirror w/ absolute position feedback
 - Frequency stabilized laser source
- Camera pixel size: 100 microns equiv. on surface to be measured
- Dedicated algorithms for wavefront extraction over $> 10^6$ pixels
- Demonstrated optical surface measurement Accuracy: $\ll 1$ nm rms
- Presently limited to optics and deformable mirrors $< 4''$ diameter
- Operates in vacuum within HCIT lower level
 - Concurrent measurement w/ other coronagraph experiments
- Now being used for detailed calibration of Xinetics DMs influence function & linearity
- User provides electronic drivers and feed-through cables



Surface Gauge bench fits into lower mezzanine of HCIT



End points of axes are [4.5,6.5] inches from table corners. Beam height = center of beamsplitter = 4.405 inches. Top of b.s. mount = 8.810. Lens cell dia = 3.480. Top of lens cell = 6.147 inches.

Surface Gauge optical layout

Large Deployable Structures Precision Environment Test Enclosure (PETE)



Facility

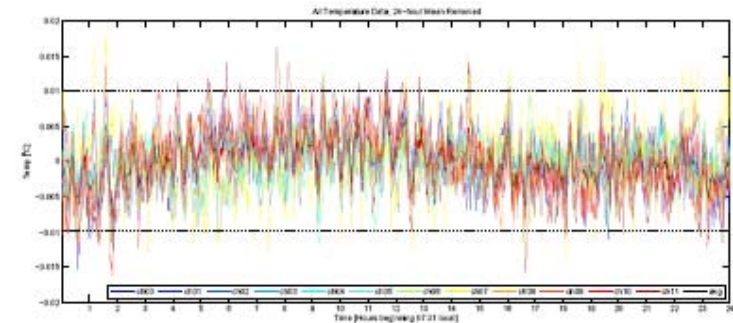
- Tests deployment accuracy and stability of large structures
- Dimensions: 10-m x 5-m x 3-m
- Stable environment for testing:
 - Thermal Stability: < 0.01 K/hr, <0.02 K/24 hrs
 - Vibration: < 75 micro-g rms (0-500 Hz)
 - Acoustics: 35 dbA
 - Relative Humidity Stability: 1%
- Cabling Pass thru for external electronics
- Active thermal control
 - < 5 min for air temperature stabilization (30 min from cold start)
 - Up to 1 KW heat load while maintaining performance
- Optical table available for additional isolation
- Class 100,000 clean room capable
- Wall and ceiling mounting possible

Measurement Capabilities

- Scanning Laser Vibrometer
- Labview data acquisition and control
 - 50 high speed simultaneous sampling for accelerometers
 - Experimental control via custom UI
- Laser Holography system for in-plane or out-of-plane deformations of 10 nm to 25 microns.
- Videometry for <0.5 mm measurements at up to 16 frames/second for 20 min.
- FLIR thermal imaging camera
- Modal test exciters and ID software.



SABUR 9-m deployable in PETE



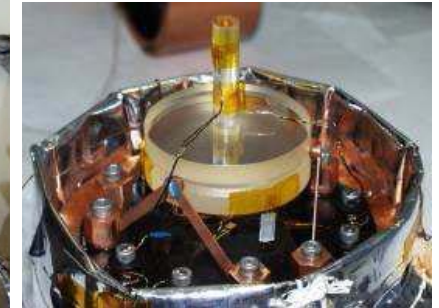
PETE Thermal Stability:
<0.02 K per 24 hrs
(with a 1 KW heat load)

JPL Cryogenic Dilatometer

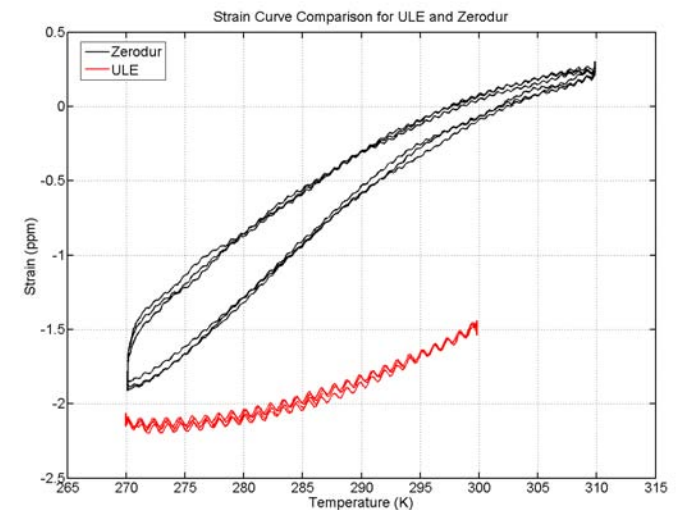


ExoPlanet Exploration Program

- Measures strain and CTE of precision materials at any temperature from 310°K to 20°K
- Vacuum facility with precision interferometer metrology system
 - Capable of ppb accuracy and repeatability (sub-nm relative elongation)
- Experiments can be performed over multiple temperature cycles
- Temperature can be maintained for very long periods to mK stability
 - For studying dimensional stability and thermal relaxation
 - Temperature cooling rate can be controlled
- Materials characterized includes: Zerodur[®], ULE[®], Single Crystal Silicon, SiC, Invar, PMN, ...
- Also used for characterizing piezo-electric actuators at cryogenic temperatures



JPL Cryogenic Dilatometer



Multiple cycles of Zerodur[®] & ULE[®] at room temperature

Exoplanet Program Point of Contact



For questions concerning use of ExEP technology
infrastructure contact:

ExoPlanet Exploration Program

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