National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

ExoPlanet Exploration Technology
(Terrestrial Planet Finder)

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Jet Propulsion Laboratory

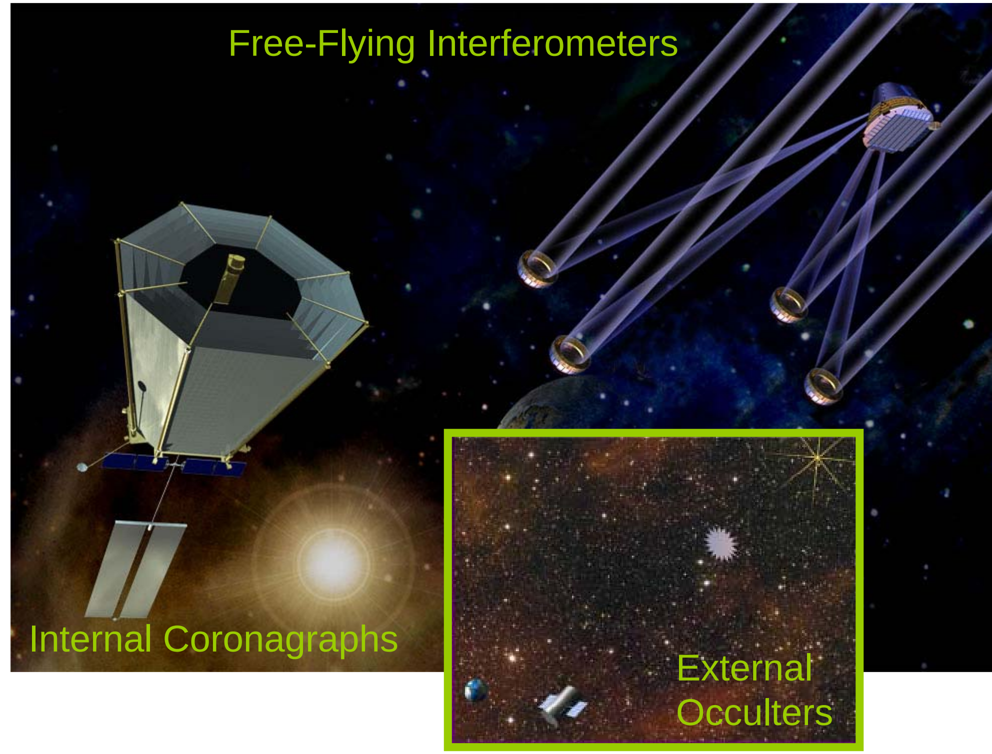
Large Space Apertures Workshop
Nov. 10-11, Caltech

Program Overview

ExoPlanet Exploration Program

Salient Features

- Two flight missions
- Visible-NIR Coronagraph and Formation Flying Mid-IR nulling Interferometer
- Starlight suppression to 10^{-10} (vis) and 10^{-5} (mid-IR)
- Flagship mission class missions ($2B+) w/ mission start >2015
- Probe-class missions w/ similar tech needs & start >2010



Science Goals

- Detect and image Earth-like planets in the “habitable zone” of nearby stars via their reflected light or thermal emission
- Characterize physical properties of detected Earth-like planets (size, orbital parameters, albedo, presence of atmosphere) and make low resolution spectral observations looking for evidence of a *habitable* planet and bio-markers such as O_2, O_3, CO_2, CH_4 and H_2O
- Detect and characterize the components of nearby planetary systems including disks, exozodiacal dust, giant planets and multiple planet systems

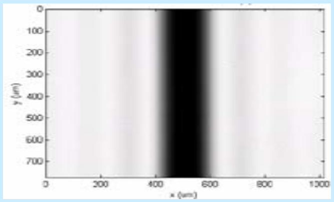
Program Status:

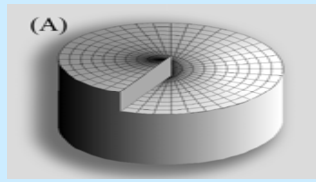
- Completed study of a viable mission concept for flagship coronagraph (FB1). Other studies in progress for probes and flagships. Decadal Survey evaluation in 2009-10. **Cost matters!**
- Currently re-planned as a Technology Program in support of near-term probe-scale exoplanet missions and longer-term flagship missions

Coronagraphy Primer

ExoPlanet Exploration Program

Image Plane Masks



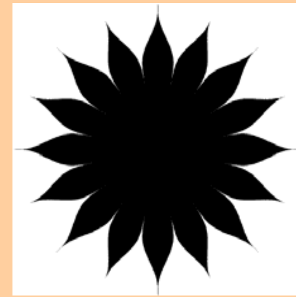


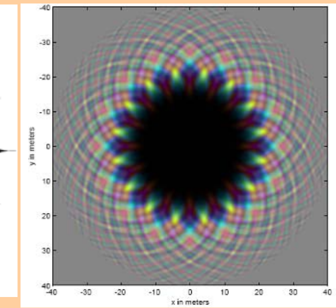
Metal Band-Limited

Vortex

Best results so far, good aberration rejection, hard to achromatize, low throughput, large inner working angle

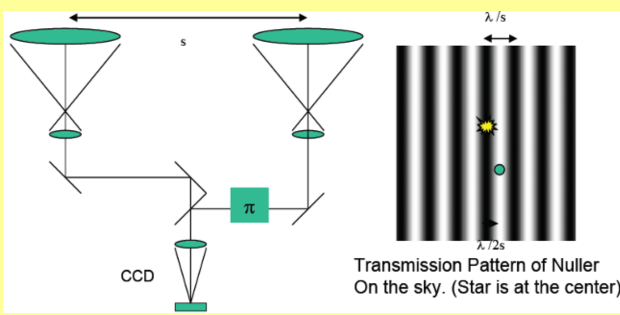
External Occulter





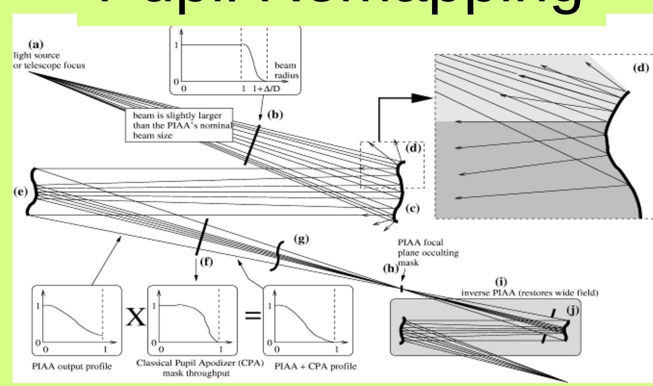
Broad band, uses standard telescope, large floppy structure, limited mobility, test scalability issues

Shearing Nulling Interferometry



Most complicated to implement, Performance.similar to band-limited mask

Pupil Remapping



Closest to ‘ideal’ high throughput, small IWA, challenging optics, unknown WFC issues. Most sensitive to stability.

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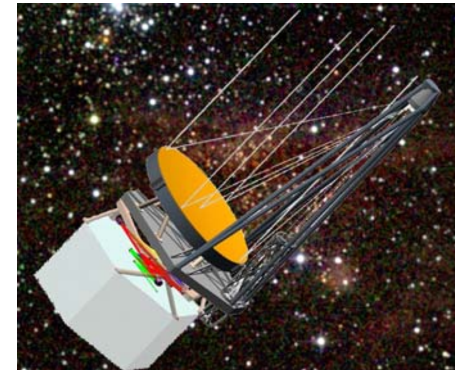
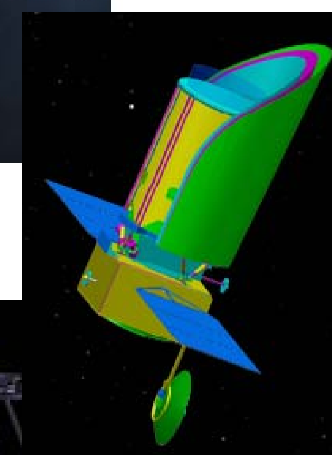
Astrophysics Strategic Mission Concept Studies: Exoplanet Exploration Missions

ExoPlanet Exploration Program

Name	Instrument	Size	PI Affiliation	Category
PECO Pupil-mapping Exoplanet Coronagraph Observer	PIAA	1.4m Telescope Medium Class	Olivier Guyon Univ of Arizona	Internal Coronagraph
ACCESS	Band-Limited Dielectric, PIAA, Shaped-Pupil, Vortex, 4QPM	1.5m Telescope Medium Class	John Trauger JPL	
XPC eXosolar Planet Characterization	Hybrid: Internal / External	4m Flagship w/ 30m Shade	David Spergel Princeton	
NWO New Worlds Observer	External Occulter	4m Flagship w/ 25m/50m Shade	Webster Cash - Univ of Colorado	External Coronagraph
DAVInCI	Dilute Aperture Visible Nuller	4x1.2m Flagship	Mike Shao JPL	Internal Coronagraph / Interferometer
EPIC	Visible Nuller	Medium Class	Mark Clampin - GSFC	
Planet Hunter	Astrometric Interferometer	Medium Class	Geoff Marcy UC Berkeley	Interferometer





This is a very vibrant community!

Mission Scale Comparisons

ExoPlanet Exploration Program

	Type	IWA* (l/Dmax)	Primary Mirror	# Earths, # Targets	# Jupiters, # Targets
Large-class Mission (> $2B)					
TPF-I	Classic-X Array	2.5	4 @ 4 m plus beam combiner spacecraft	190, 380	440, 460
TPF-C	Flight Baseline - 1	4	8 m x 3.5 m	41, 85	390, 680
TPF-C	Flight Baseline - 1 with Pupil Mapping (PIAA)	4	8 m x 3.5 m	73, 140	580, 800
Mid-class Mission (< $2B)					
TPF-I	Emma-X Array	2.5	4 @ 2 m plus beam combiner spacecraft	70,150	160, 190
TPF-C	Band Limited Mask, Shaped Pupil or Visible Nuller	3.5	4 m	19, 36	320, 540
TPF-C	Pupil Mapping (PIAA)	3.5	4 m	25, 56	460, 580
TPF-C	Pupil Mapping (PIAA)	2.5	4 m, aggressive IWA	48, 99	550, 710
TFF-O	External Occultor	~2.5	4 m telescope + 50 m occulter @ 72000 km	28, 64	70, 78
Probe-class Mission (< $1B)					
TPF-C	Band Limited Mask, Shaped Pupil or Visible Nuller	3.5	2.5 m	6, 13	130, 240
TPF-C	Pupil Mapping (PIAA)	3.5	2.5 m	7, 15	230, 380
TPF-C	Pupil Mapping (PIAA)	2.5	2.5 m, aggressive IWA	16, 29	290,470

How Challenging is Direct Detection of Terrestrial Planets in Visible Light?

Imagine taking a picture of a bump 1/100 the thickness of a human hair…

…on the top of Mt. Everest!!

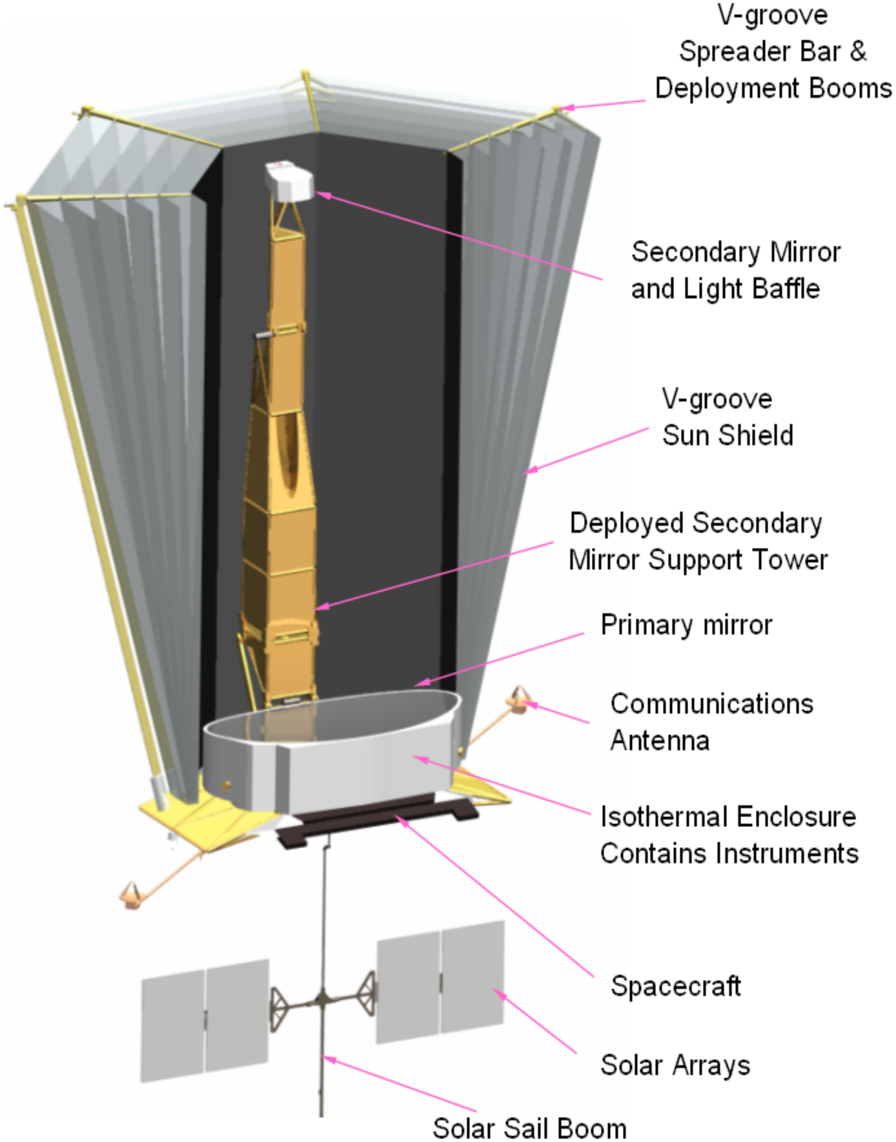
90 microns / 100 = $9e^{-7}$ m

9000 m = $9e^{3}$ m

That's a ratio of $1e^{-10}$, same as Earth to Sun contrast!!

TPF-C Flagship Mission – Flight Baseline 1:
Feasible w/ Existing Launch Vehicles and Test Facilities

ExoPlanet Exploration Program



Instrument
- Band-Limited 8^{th} Order Mask, $<10^{-10}$ Contrast
- IWA =60 mas = 4 λ/D
- Modest Throughput

Design
- 8m x 3.5m primary mirror
- Monolithic, Off-axis, Unobstructed
- Deployable SM tower, 10m tall
- Deployable V-groove sun-shield
- Active isolation
- Active/passive thermal control
- 2 deformable mirrors for wavefront control
- Fits in existing Delta-4H launch vehicle

Stability Requirements
- 4 mas rigid body pointing
- PM figure 400pm at low spatial frequencies & 5pm at high spatial freqs beyond WFC
- SM Despace Thermal= 26nm, jitter = 1.3nm
- Thermal stability during observation ~0.1mK

Models & Detailed Engineering Studies
- Error Budget tools to flow down reqs
- Instrument models w/ WFSC, diffraction
- Integrated models: jitter, transients, Δ CTEs
- Mission models for science simulations

Outcome;
- No show-stoppers. Requirements are met
- Image 41 Earths, 390 Jupiters

ExEP Critical Technologies

Lifecycle costs includes Technology Development

- **Starlight Suppression**
  - Laboratory demonstrations
  - Masks & Occulters
  - Optical scaling (external occulter)
- **Wavefront Control**
  - Nulling algorithms
  - Deformable mirrors
- **Pointing Control & Navigation**
  - Vibration isolation & control
  - Formation flying
- **Verification and Validation**
  - Optical diffraction modeling
  - Opto-thermal-mechanical (integrated modeling)
  - Scaling: size, loads, environment
  - Model validation and predictability
- **Precision Optics**
  - Large light weight @ diffraction limit
  - Low CTE telescope materials
  - Metrology systems
- **Stable (Deployable) Structures**
  - Milli-K thermal control & predictions
  - Microdynamics & nonlinearities
  - Mechanisms
  - Precision material characterization
  - Cryogenic structures

Interferometer Planet Detection Testbed

Coronagraph High Contrast Imaging Testbed (HCIT)

Coronagraph Technology Maturity Summary: *Community Consensus (2008 Exoplanet Forum)*

Internal Coronagraph		1.5m Telescope @ 4λ/D	1.5m Telescope @ 2λ/D	4m Telescope @ 4λ/D	8m Telescope @ 4λ/D
Coronagraph Instrument Technologies	Raw Contrast at IWA *(Laboratory Demos)*	1e-10 @ 10-20% bandwidth	1e-10 @ 10-20% bandwidth	1e-10 @ 10-20% bandwidth	1e-10 @ 10-20% bandwidth
	DMs				
	WFSC Algorithms				
	Masks				
Telescope & Mirror Technology					
Modeling Tools & Validation	Optical				
	Integrated: Opto-Thermal Mechanical				
Pointing		0.5 mas	0.5 mas	0.5 mas	0.5 mas
Thermal Control		0.1mK	0.1mK	0.1mK	0.5 mK
Detectors					
System Verification & Validation					

External Coronagraph		1.1 m Telescope w/15 m Starshade	Existing Telescope w/ 50m Starshade	4m Telescope w/ 50m Starshade	4m Hybrid w/ 36m Starshade
Occulter Raw Contrast *(laboratory demo)*		1e-8 @ 100% bandwidth	1e-10 @ 100% bandwidth	1e-10 @ 100% bandwidth	1e-10 @ 100% bandwidth
Occulter Deployment & Tolerance	Petal Position Errors	0.5 m	0.1 m	0.1 m	0.1 m
	Shape Error	5 mm	2 mm	2 mm	2 mm
	Edge Effects	~1 cm	<1 mm	<1 mm	<1 cm
Telescope & Mirror Technology					
Modeling Tools & Validation	Optical & Scaling				
	Integrated Opto-Thermal Mechanical				
Formation Flying		±1 m	±1 m	±1 m	±0.1 m
Internal Coronagraph		N/A	N/A	N/A	1 e-4
Occulter Thermal Control		~5 K	~5 K	~ 5 K	~5 K
Detectors					
System Verification & Validation					

- **Assessment of the main technologies for internal & external coronagraphs as a function of scale: size and inner working angle (IWA) – irrespective of science return / merit**
- **Colors represent technology risk and maturity as an indication of development need.**
- **Numerical values, where appropriate, represent performance goals for flight.**
- **Columns correspond to representative mission concepts, and are not an exhaustive list of possibilities.**

Starlight Suppression Results to Date

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Contrast Starlight Suppression | *Technique*

10^{-5}
- Optical vortex monochromatic @ 2λ/D in air (Arizona/JPL)
- Visible nuller 15% bandwidth @ 3.5λ/D in air (JPL)

10^{-6}
- PIAA monochromatic @ 2λ/D in air (Subaru)
- Visible nuller monochromatic @ 3.5λ/D (JPL)

10^{-7}
- External Occulter broadband @ 2λ/D in air (Uof Colo)

10^{-8}

Approximate Range of Detectability
Jupiter
↓
Earth

- Shaped pupil 10% bandwidth @ 4λ/D in vac (Princeton/HCIT)
- Shaped pupil mask 2% @ 4λ/D in vac. (Princeton/HCIT)

10^{-9}

TECHNOLOGY MILESTONE LEVEL

- 4th order Metallic 10% bandwidth @ 3λ/D in vac (JPL/HCIT)
- 4th order Metallic 10% bandwidth @ 4λ/D in vac (JPL/HCIT)
- 4th order band limited monochromtic @ 4λ/D in vac (JPL/HCIT)

10^{-10}

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HCIT Starlight Suppression Milestones

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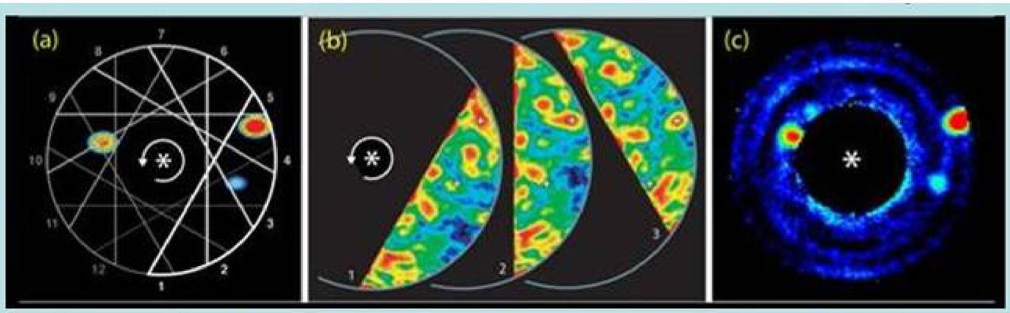
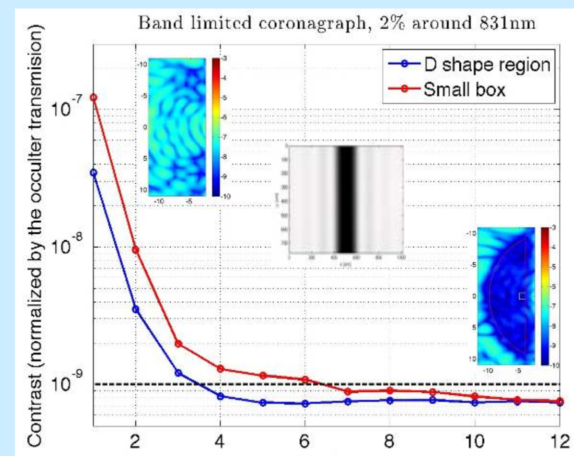
Technology	Specs	Performance to date	Performance to date (*Preliminary Results*)	Performance target prior to Phase A	Flight Performance (preliminary)
Contrast	Average contrast (4 to 5 λ /D)	3.6×10^{-10}	5×10^{-10} (10%BW)	Less than 1×10^{-9}	Less than 1×10^{-10}
	Average contrast (4 to 10 λ /D)	3.8×10^{-10}	8×10^{-10} (10%BW)	Less than 1×10^{-9}	Less than 1×10^{-10}
	Bandpass	mono-chromatic	80nm	60 nm	100 nm
	Wave length range	0.785 µm	760nm-840nm	0.5 to 0.8 µm	0.5 to 0.8 µm



HCIT testbed results demonstrates contrast at levels required to detect earth-twin (*Nature*, April 2007)

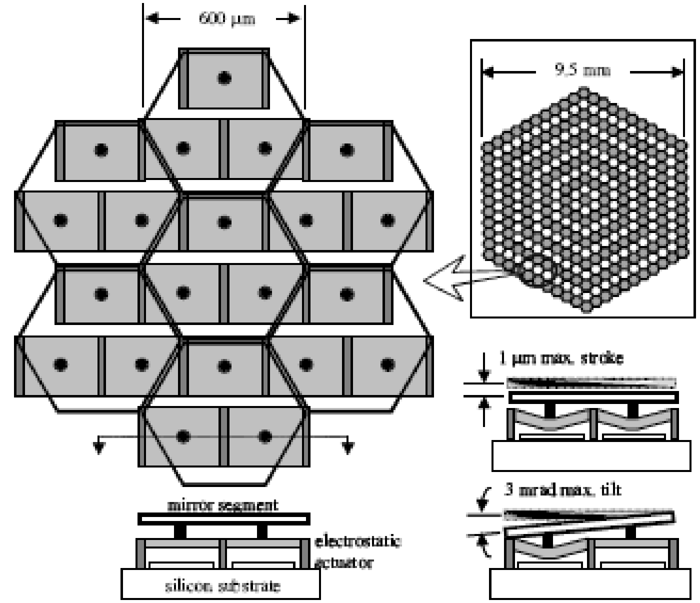


- Recent results for Ni metallic mask for 3λ/D & 20% BW
  - Contrast ~2e-9
- Testing of Pupil Remapping Coronagraph in preparation

Electric Field Conjugation method improves nulling convergence (*Give'on, SPIE 6691-09*)

Deformable Mirrors

Gen2 64x64 mm DM delivered to JPL. The same 32x32 actuator technology is repeated four times, bonded together, with a single facesheet.



64x64 mm Xinetics DM
PMN electro ceramic blocks
4086 actuators @ 1mm pitch
100V range w/ 16-bit resolution
Surface figure ~1nm
Active WF control ~0.01nm RMS
Actuator stroke ~ 200nm
TRL ~5

9x12mm Boston Micromachines
3-layer MEMs DM Design for TPF
(Stewart et al. SPIE 4113-24, 2006)
331 hexagonal mirror segments, each supported by electrostatic actuators
Surface figure ~10nm
Active WF control ~10nm
Actuator stroke ~ 2μm
TRL~3

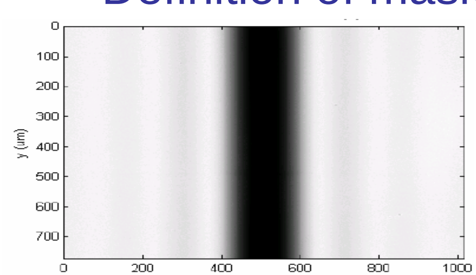
Mask Technology

***Informed model-based design and fabrication process*:**

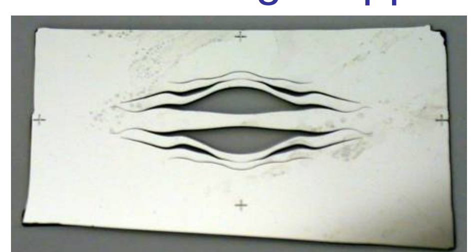
- Band-limited mask Phase vs Optical Density for optimal broadband contrast, including contributions from WFC method and optical aberrations

  Sidick (SPIE, 6693-49, 50), Moody (SPIE 6693-57)
- Design of new metallic masks for broadband performance >30%

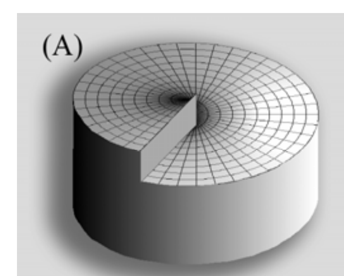
  Balasubramarian (SPIE 6693-37)
- Verification of mask models using HCIT test results *Trauger (SPIE 6693-35)*
- On-site fabrication & characterization of precision masks at JPL Micro-Devices Lab
- Fabrication tolerancing and impact on contrast performance
  - Princeton Shaped-pupil mask experiments (*Belikov, SPIE 6693-36*)
  - UofA/JPL Vortex mask *(Palacios, SPIE 6693-28)*
- Definition of mask requirements for flight applications



BL HEBS GI85
4th order mask



Shape-pupil mask



Vortex mask

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Integrated Modeling for Large Apertures

TPF-C Observatory Simulation: Thermal Stability of 20º Dither

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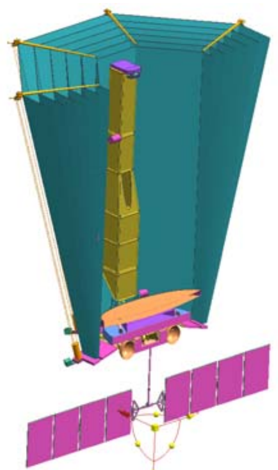
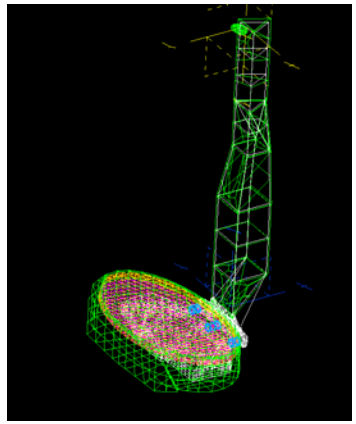
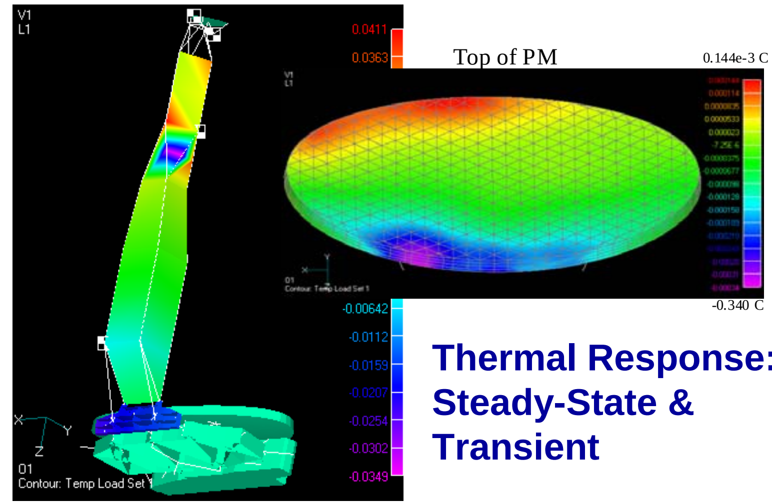


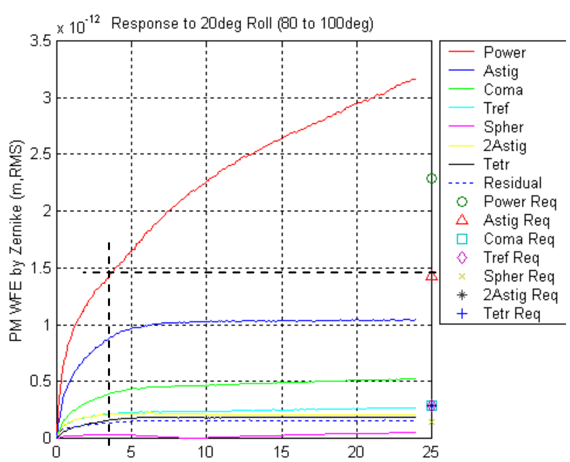
Mechanical Design



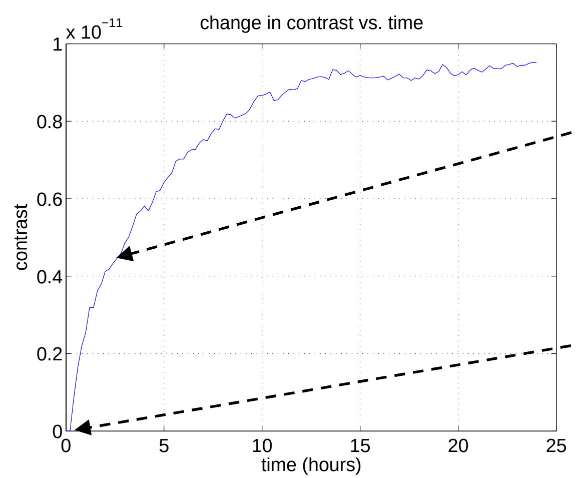
Common Mesh: Thermal, Mech & Optical



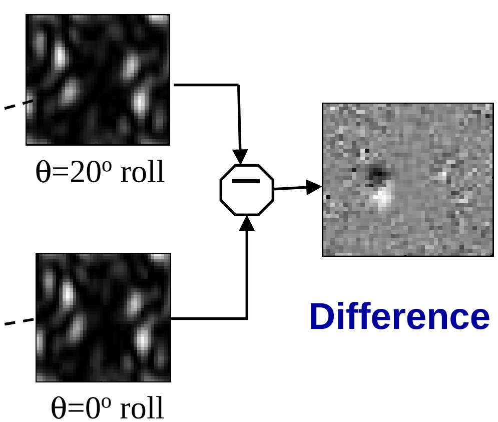
Thermal Response: Steady-State & Transient



Transient WFE decomposed into 15 Zernikes vs. Reqmts.



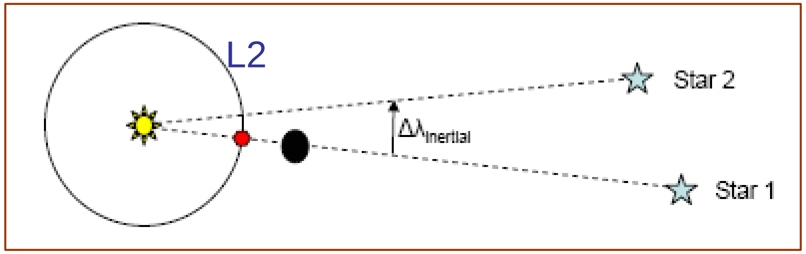
Transient Contrast after 20deg dither



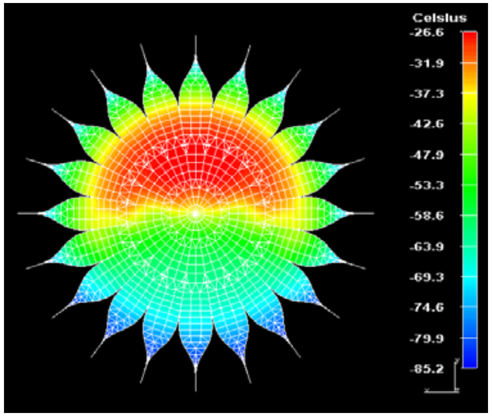
Difference

Speckle Removal for Planet Detection

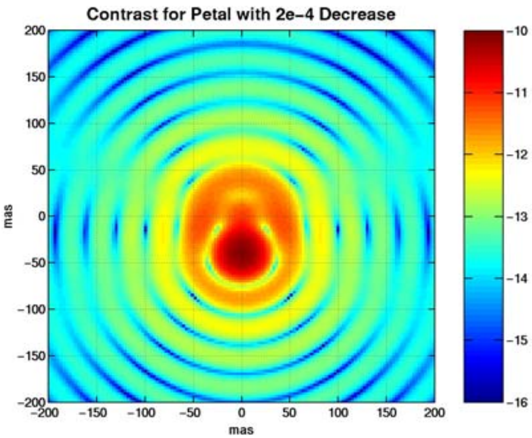
Modeling for External Occulters



- **Navigation & Propulsion**
  - ΔV for station keeping & repointing
  - Formation flying & alignment
  - Trajectory options, propulsion system studies
- **Science simulations & capabilities**
  - # of stars visited, #planets, # revisits
- **Large scale effective optical diffraction tools**
  - Tolerancing and scaling
- **Integrated modeling**
  - Thermal and Jitter analyses
  - Impact on contrast performance
- **Sub-scale External Occulter mask fabrication**
  - Issue w/ how to scale results from 10cm to 50m



Temperatures at the front-side of Occulter w/ sun at 5^o (20 petals, 54 m tip-to-tip)



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

Multi-Scale & Multi-Physics Modeling for Large Apertures

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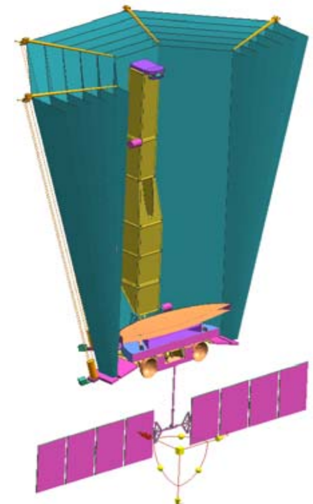
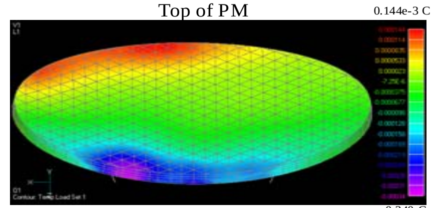
System Level
Thermal-Structural-Optical Aberrations
Stability, Performance, System Control,
Design Optimization



Component Level
Thermal-Structural-Optical-Control
Optical Diffraction Propagation
Nonlinear Continuum Mechanics

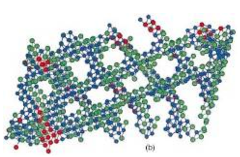


Test Correlation with Data Acquisition and Code Validation with Experiments

Apply Environmental Loads: Thermal & Jitter

Steady-state
Transient
&
Dynamic
Simulations

Molecular Level
Nanoscale
Material Models,
Micro-Dynamics
Photon Effects,
Nanolayers,
Friction



Conversion of Microscale Mechanics Tests & Simulations into Continuum Mechanics Models

< nm wavefront error predictions

Bounding analysis including modeling error margins within error budget performance allocation

nm mm m

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Precision Materials Characterization

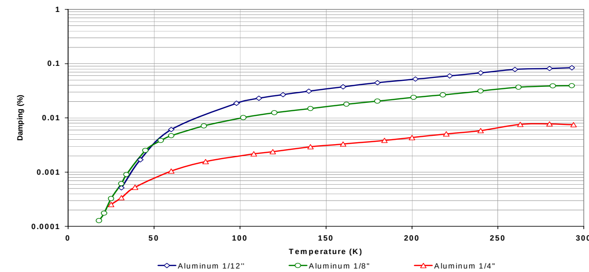
ExoPlanet Exploration Program

Strategic Importance & Applications

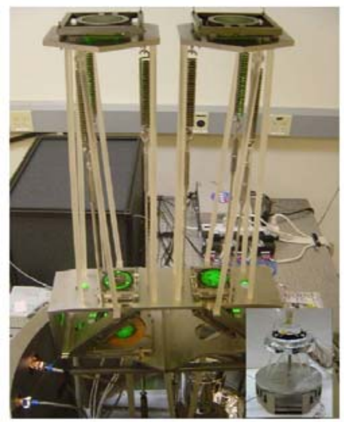
- Characterize nanometric material performance from room temperature to cryo 20ºK at unprecedented levels of precision & dimensional stability
- Enable high fidelity analysis for large precision cryogenic systems which cannot be otherwise tested on the ground
- Unique ability to maintain & control temperature to 5ºmK
- Targeted opportunities:

  JWST, TPF, SAFIR, Large Deployable Apertures, Precision Cryo Systems, etc..

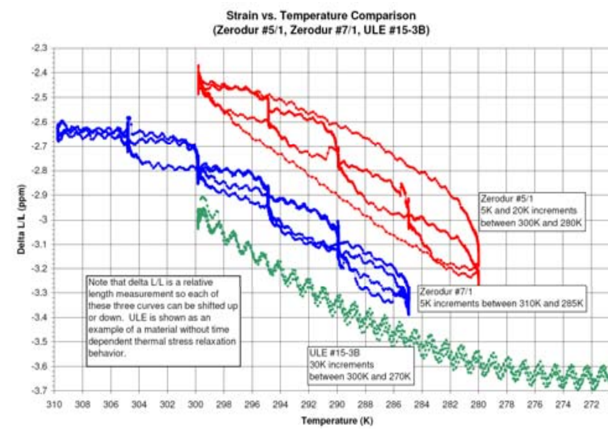
Cryo Damping



Database of material cryo damping – some as low as 10^{-6} at 20ºK – correlation to Zener models at RT

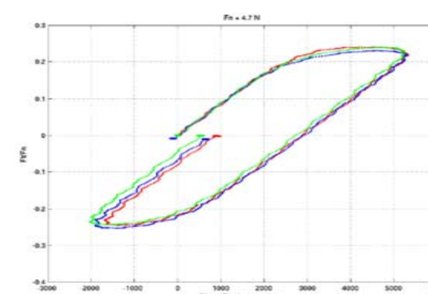


Cryo Dilatometer



Nonlinear thermal strain of Zerodur vs linear ULE

Cryo Tribometer

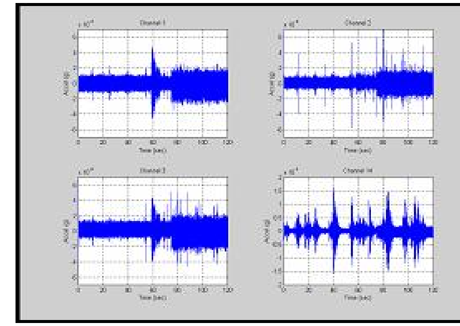


Extract Microslip coeff of friction using Mindlin models for Hertzian contact

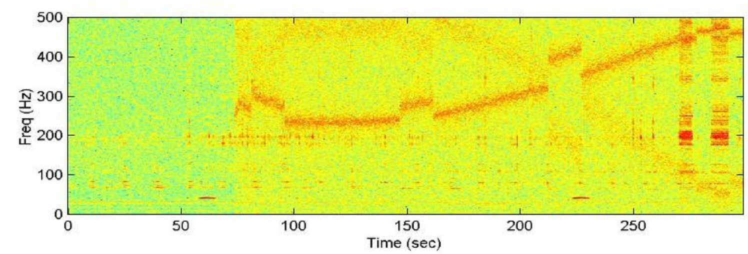
What do we know to date about precision stability of structures?

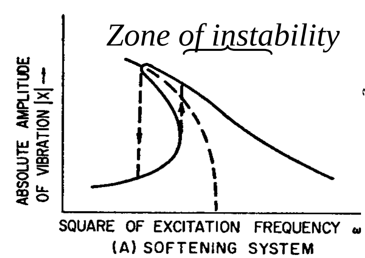
ExoPlanet Exploration Program

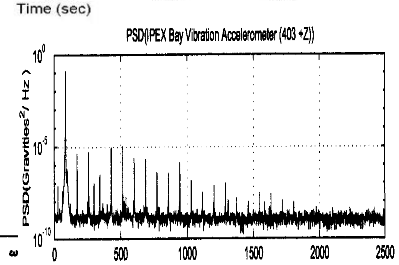
- **IPEX flight experiments demonstrated: (1997-98)**
  - Different dynamics in 0G vs 1G
  - Spontaneous vibrations from strain energy release stored in frictional mechanisms

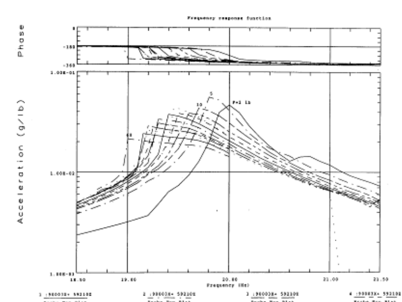


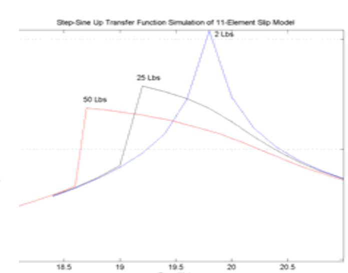
- **Microdynamics Technology (w/ CU)**
  - Modal variation (f, ζ) as a function of time, amplitude, load history
  - Harmonic distortion of frictional interfaces
  - Uncertainty in static equilibrium (micro-lurch & multiple equilibrium zones – Warren & Hinkle)
  - Design guidelines to minimize hysteresis, and to manage load path (w/ Hachkowski, Lake)
  - Preliminary attempts to validate constitutive models for hysteretic behavior (Iwan models)







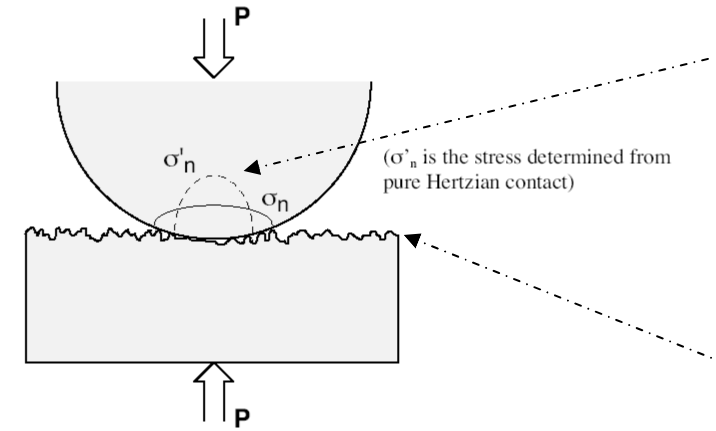




Microslip in Nonconforming Contact Mechanics: Defining the Constitutive Behavior

(Peterson & Hinkle, University of Colorado, Boulder)

ExoPlanet Exploration Program



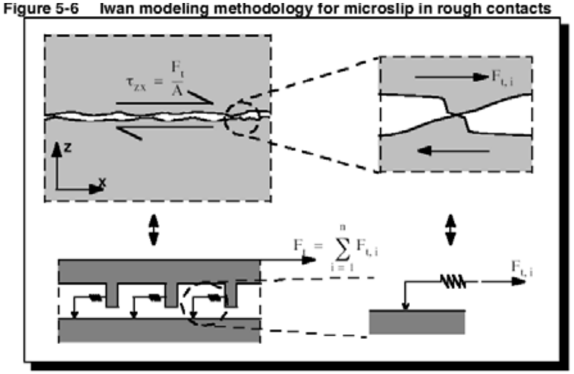
Stress Gradient induced Microslip due to stress distribution at edge of contact from pure Hertzian contact

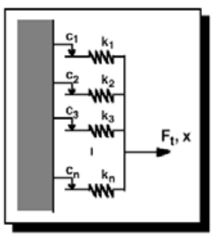
shear displacement
$$\delta_x = C_o\left(1-\left(1-F^*\right)^{\gamma}\right)$$

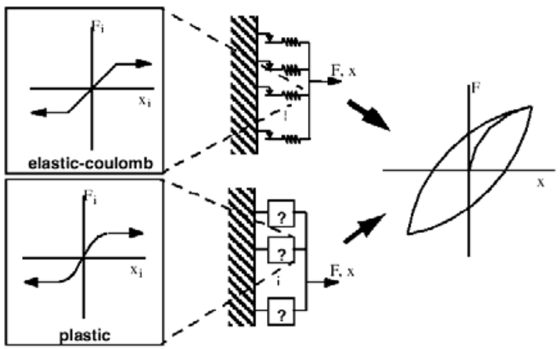
normal load, $F^* = \mu P$
sliding sphere, $\gamma = 2/3$
coefficient of friction μ,

Micro-roughness induced Microslip from asperities

Figure 5-6 Iwan modeling methodology for microslip in rough contacts







Driving Physical Parameters of Constitutive Equation:

- Stress distribution & loads at interface
- Micro-friction coefficient
- Interface stiffness
- Surface micro roughness

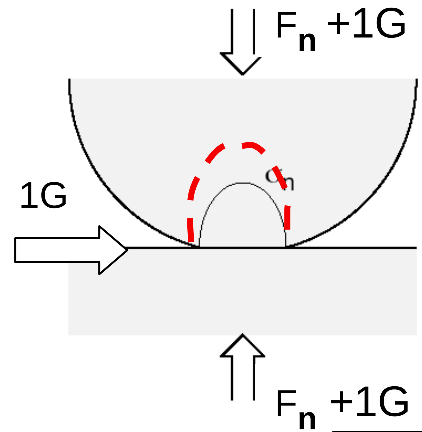
Constitutive Hysteretic Behavior Defines:

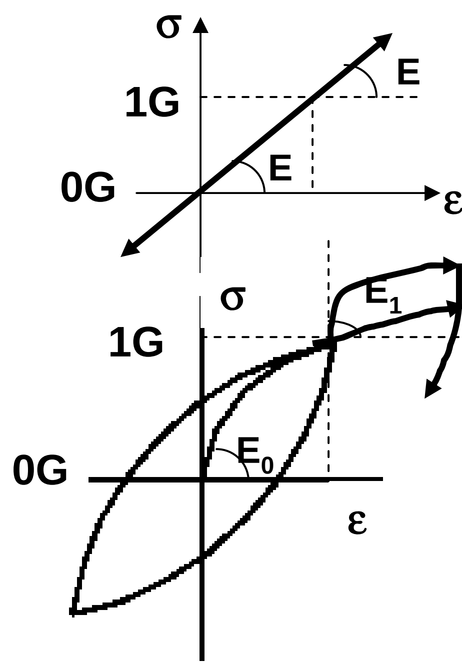
- Stored strain energy capacity
- Frequency response instability and harmonic distortion
- “Component damping”

Scaling 1-G to 0-G:

Standard 1g analysis applies external uniform load and ignores internal stress-strain physics

- **Will impact the contact mechanics**
  - Impacts microslip by changing stress gradient at interface
  - Or induce shear across the interface
- **Will impact the internal stress-strain state of the material:**
  - If the material is linear, the stiffness is unchanged
  - If the material is non-linear, 1G field will bias the stress-strain response and stiffness might change
  - The question is how much?
    - can only be answered through a flight experiment.
    - anecdotal evidence from various flight projects that this does matter
    - must be bounded in the analysis





Stiffness of linear syst is insensitive to load, amplitude and direction. Only 1 unique state per load.

Stiffness of nonlinear syst is sensitive to load history, amplitude, and direction.
Multiple states per load creates dynamic response instability & harmonic distortion

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Near Term Activities

ExoPlanet Exploration Program

Technical

- Continue Starlight Suppression Demonstrations (HCIT)
- Improve Wavefront Sensing & Control capabilities
- Study polarization effects
- Calibrate DMs
- Fabricate and test sub-scale external occulting masks
- Implement integrated models on ASMCS mission concepts

Programmatic

- Review ASMCS recommended technologies
  - Assess technology distances and needs
  - Provide recommendations to NASA HQ
- Formulate Exoplanet Exploration (ExEP) Technology plan
  - Draft #1 released Jan’09
- Release ExEP technology RFP’s for long term mission needs
  - Expected FY’10 , budget TBD
- Release AO for ExEP probe scale mission ($600M - $800M)
  - Expected late FY’09 to FY’10
  - Opportunity for technology development funds as Category 3 mission
- Mission concepts to be presented to the Decadal Survey in ~2010
  - Recommendations on science, missions and technology
  - Credibility of cost is major concern

On-line References

- Terrestrial Planet Finder Missions (Coronagraph & Interferometers)
  http://planetquest.jpl.nasa.gov/TPF/tpf_index.cfm
- TPF-C Flight Baseline 1 Design and Validation
  http://planetquest.jpl.nasa.gov/documents/TPFC-FB1_Report.pdf
- Science and Technology Definition Team Report
  http://planetquest.jpl.nasa.gov/TPF/STDT_Report_Final_Ex2FF86A.pdf
- Coronagraph Technology Plan (2005)
  http://planetquest.jpl.nasa.gov/TPF/TPF-CTechPlan.pdf

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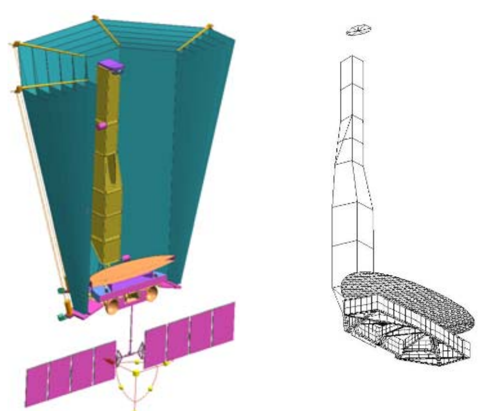
Integrated Modeling: What is Cielo ? (Claus Hoff)

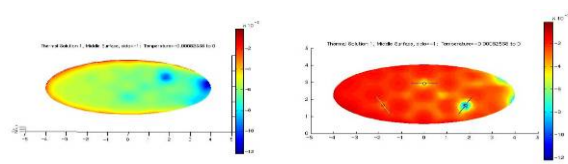
ExoPlanet Exploration Program

- General-purpose finite element-based computational tool for multi-physics analysis
- Provides integrated thermal, structural and optical aberration capabilities using a common model
- Nastran input file driven
- Matlab hosted
- Running on serial and parallel machines
- Extensible object-based architecture

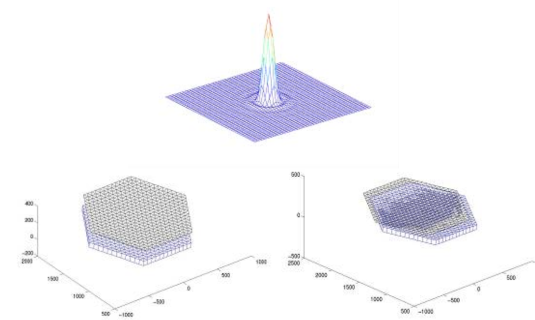
Integrated analysis capability facilitates development of detailed system-level model …



Propagates thermal, structural & dynamic effects down to optical elements and mounts …



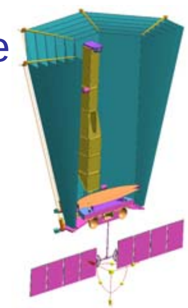
And computes aberrations from which optical merit functions & sensitivity matrices can be assessed and optimized…

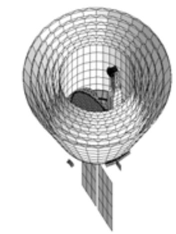


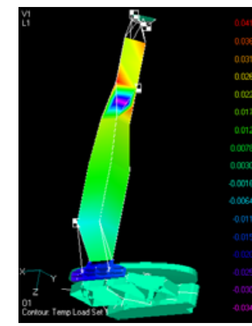
Motivation

Overcome current limitations in precision deployable structures analysis:

- COTS-based tools are domain-specific (“bucket brigade approach)
- Pre-flight, system-level hardware testing at operating conditions is impractical
- Analysis fidelity (millikelvin, picometers) proving to be a significant challenge
- In-flight real time simulations not feasible with COTS tools

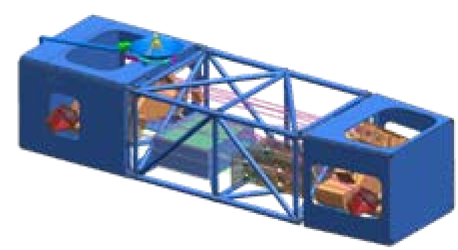


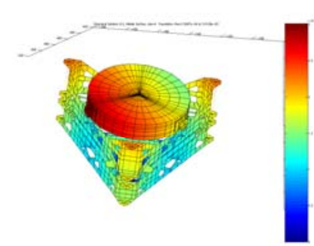




Enable analysis-driven systems engineering and design:

- Turnaround time improvement via common model approach
- Analysis fidelity via parallel computing
- Targeted methods development
- Integration with other domains (e.g. controls, optics) via MATLAB-hosting.





Backup Slides

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Overview of Coronagraph Technology

ExoPlanet Exploration Program

Goals

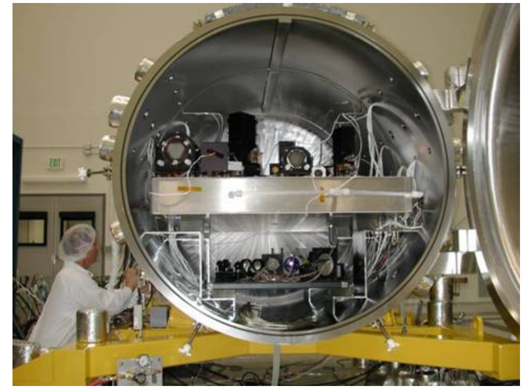
- **National infrastructure for demo of starlight suppression technologies traceable to flight**
- **Demonstrate Wavefront sensing & control technology, including deformable mirrors**
- **Develop nulling algorithm software**
- **Design & fab novel masks and shaped pupils**
- **Develop & validate modeling tools**

Accomplishments

- **Technology Milestone 1 Approved June 2006**:
  Demo 10^{-9} contrast for monochromatic
- **Technology Milestone 2 (M2) White Paper Approved Dec 2006:**
  Demo 10^{-9} contrast at 10% bandwidth (BW) light
- **Demo Earth-detection levels <10^{-9} at 2% BW April 2007**
- **Technology Milestone 2 reached April 2008**:
  Demo 10^{-9} contrast for 10% broadband @ 800nm
- **Nulling algorithms converge in <5 iterations**
- **Tested Princeton Shape Pupil coronagraph**
- **Received PIAA-1 mirrors for testing.**

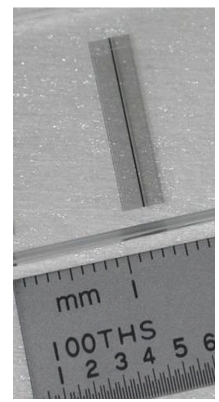
Plans

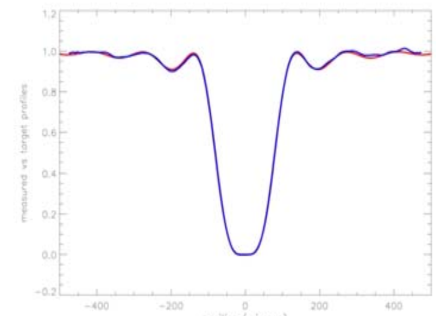
- **Fabricate shaped pupil, metallic band-limited masks, PIAA occulters, and test on HCIT**
- **Continue testing to M2 goal of 10^{-9} at 10% BW**
- **Validate models of testbed results: Milestone 3**
- **Support ASMCS tech demos: XPC, PECO, ACCESS**



High Contrast Imaging Testbed (HCIT)

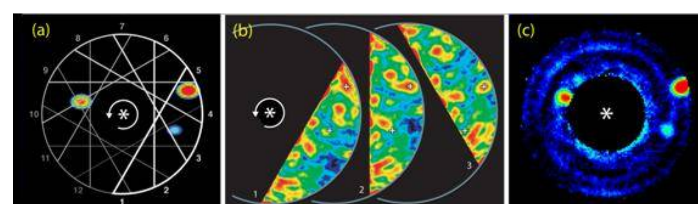
64x64 Deformable Mirror (Xinetics,JPL)





Measured transmittance --- vs model specified profile ---

4th Order Band-Limited Metallic Mask



HCIT results demonstrates contrast at levels required to detect earth-twin (Nature, April 2007)

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Technology Implementation Approach

ExoPlanet Exploration Program

Critical Technology is Ready

Pre-Phase A — Physics & Materials

Phase A — Components

Phase B-C-D — System

Characterize Physics

Develop & Validate Modeling Tools

Establish Tech Milestones

Error budget Flowdown Reqs w/ Margins

Determine Sensitivity of Parameters on Contrast, WFE

Apply Physics & Analysis to Preliminary Design

Develop V&V Reqs

Develop System & Component Design

Test & Validate Component Models

Assess Uncertainties

Verify E2E System Performance By Analysis

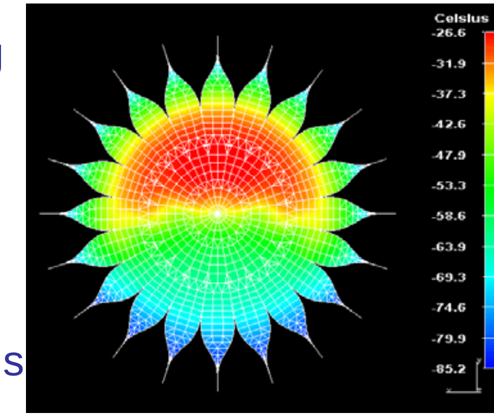
Technology Demonstration Testbeds:
Design, build, & test progressively higher levels of assembly
Starting w/ composite coupons to Subassemblies
Full scale vs. Sub-scale

Modeling Technologies

ExoPlanet Exploration Program

Optical Model of HCIT Starlight Suppression System

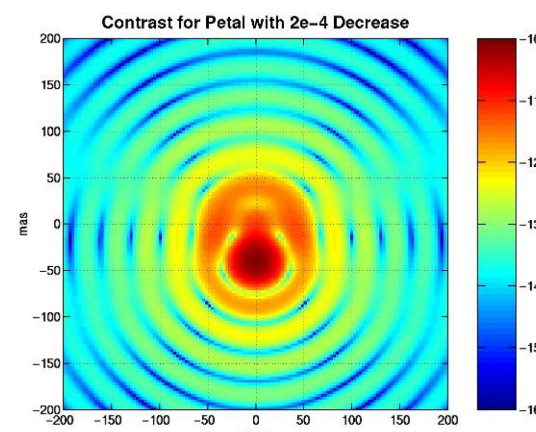
- Uses JPL in-house code MACOS for diffraction modeling
- Applicable to any of the internal coronagraph options
- Links optical figure and alignment tolerances to contrast requirements
- Incorporates deformable mirrors and WFS&C algorithms
- Will to be used to test algorithms, identify experimental errors, build testbed error budget and validate test models



Temperatures at the front-side of Occulter w/ sun at 5º (20 petals, 54 m tip-to-tip)

Integrated models of External Occulters

- Large scale optical diffraction models to simulate the effect of petal deformations and imperfections on contrast
  - Models built for representative design and validated against Princeton (XPC) results
- Thermo-mechanical finite element models using in-house integrated analysis code CIELO
  - Models built for representative 3-layer flat occulter
  - Check-out for consistency
  - Simulations show temperature gradients of ~ 100ºC
  - Waiting for actual XPC thermal and structural designs
- Seamless hand-off of structural deformation data to optical contrast analysis.

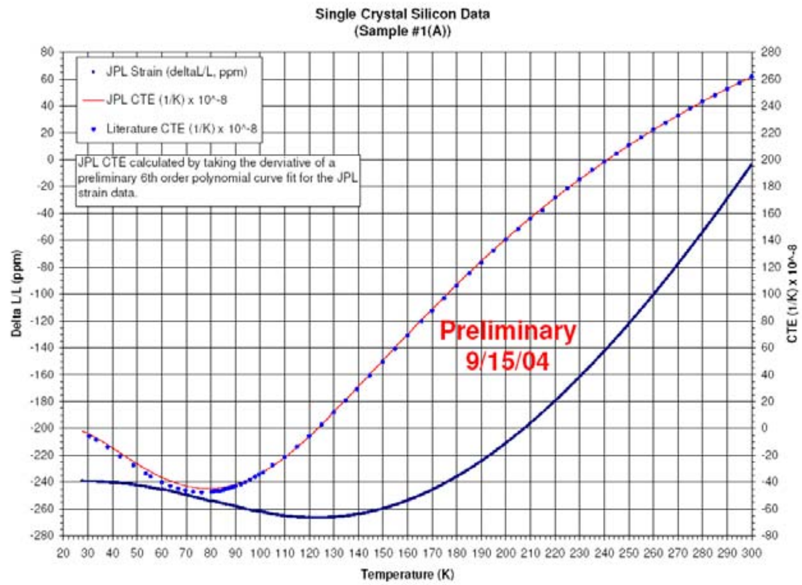


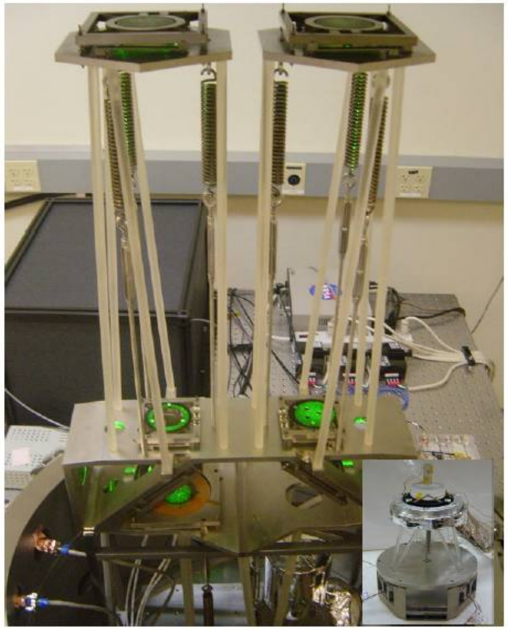
Contrast degradation due to 1mm width change in a single petal (20 petals, 54m tip-tip occulter)

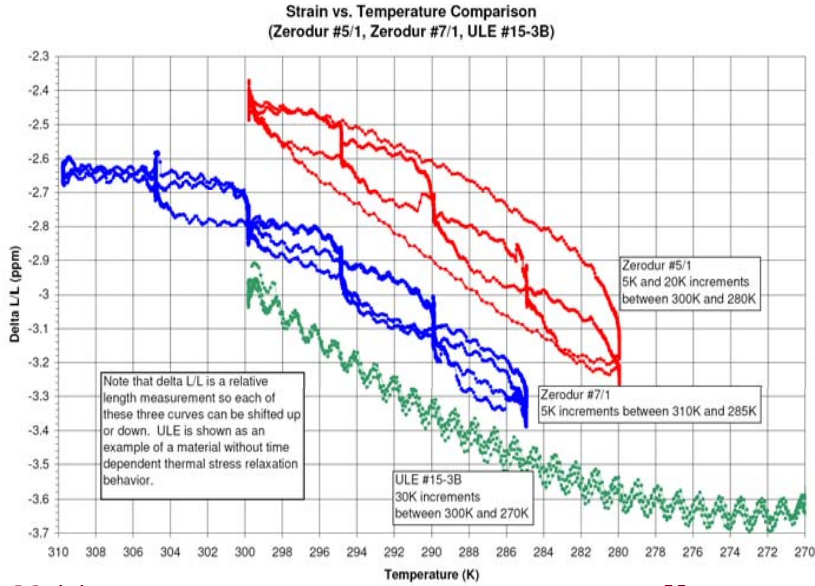
Material Stability: JPL Precision Cryo-Dilatometer

ExoPlanet Exploration Program

- Measures CTE, thermal relaxation and creep fo precision materials
- High precision strain measurement capability (ppb) using SIM derived pm interferometer metrology.
- Test temperature range of RT to 20ºK
- Cryogenic cooling through mechanical pump
- Thermal control capability (10mK) enabling lon term stability measurement at any prescribed temperature and for any cooling/warming rate

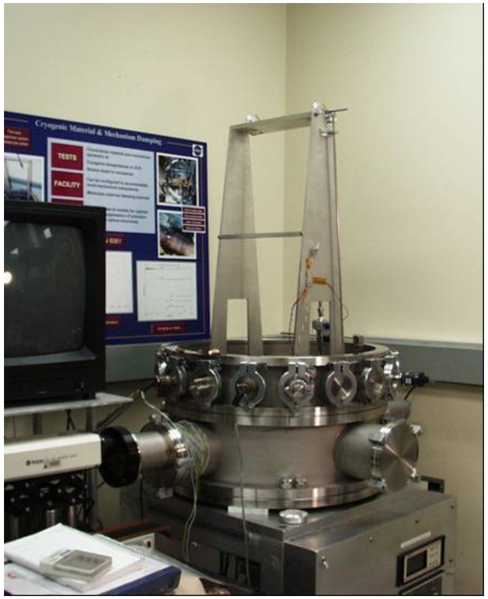




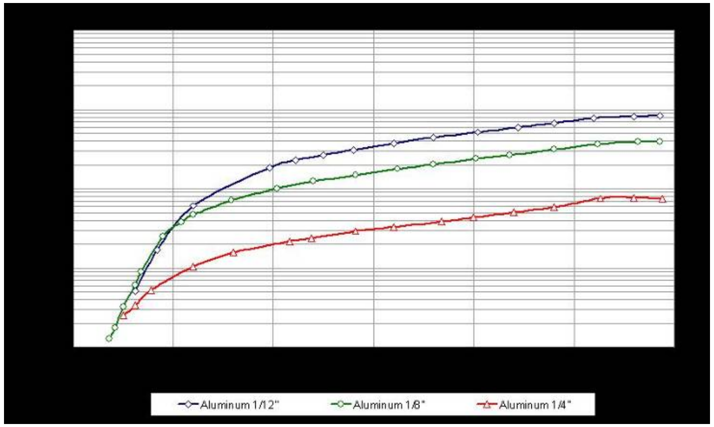


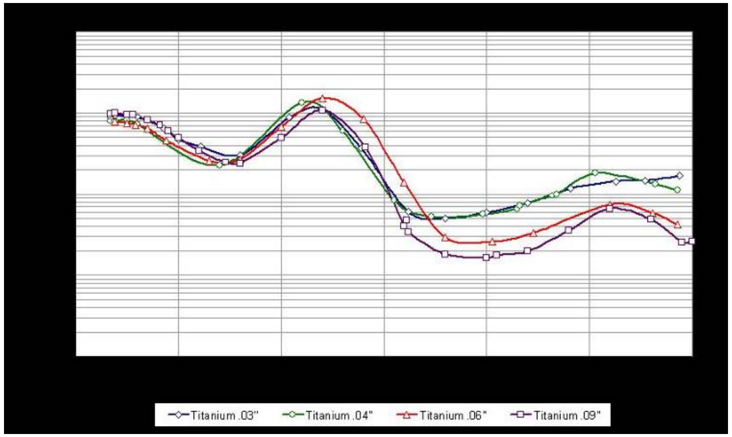
Cryogenic Material Damping

- Measures material damping and frequency from RT to 20ºK down to nanostrain levels
- Uses laser vibrometer metrology
- Developed extensive database for flight optics relevant materials as a function of frequency and temperature
- Damping at cryo as low as 10^{-4}% for Al and BeO30, and as high as 0.1% for Ti 15-3-3-3
- Validated Zener damping models at RT



$$\xi = \frac{\alpha^2 ET}{2C_p\rho}\left[\frac{\omega\tau}{1+(\omega\tau)^2}\right] \qquad \tau = \frac{C_p h^2 \rho}{\kappa\pi^2}$$





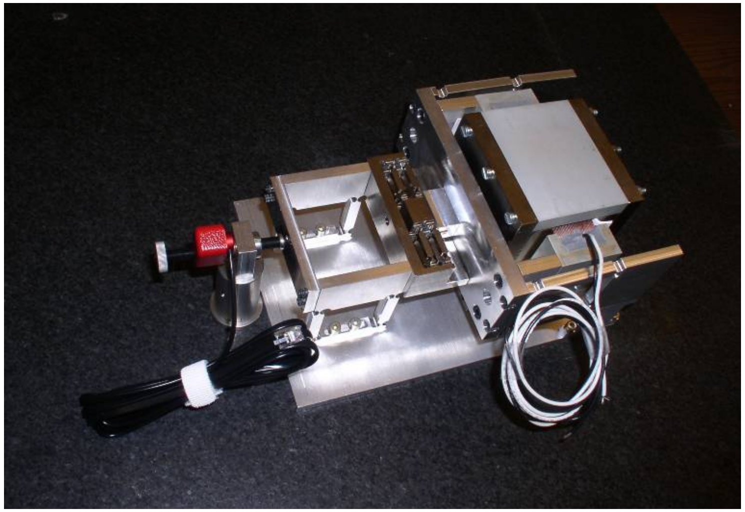
JPL Cryo-Tribometer- Microslip Results

(in collaboration w/ J. Hinkle, University of Colorado, Boulder)

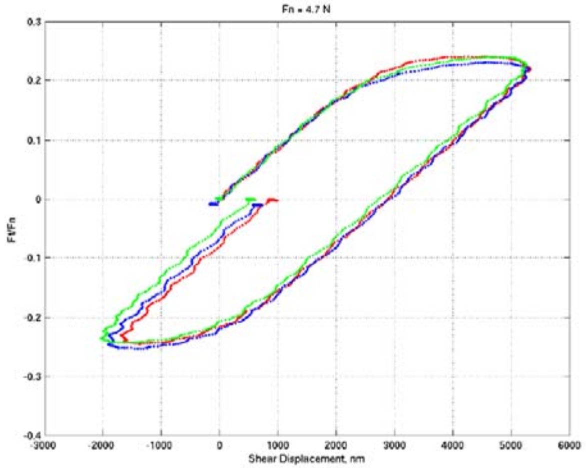
- Measures microslip motions as a function of normal preload, shear load and temperature in non-conforming interface for a variety of material.
- Picomotor induces shear load and controls shear rate
- Motion detected by eddy current sensors w/ nanometer accuracy
- Thermal control capability from RT to 20ºK
- Will build database of micro-coefficient of friction (μ) for a variety of flight mechanism materials
- μ extracted from Mindlin models for Hertzian contacts

$$\delta_x = C_o\left(1-\left(1-F^*\right)^\gamma\right)$$

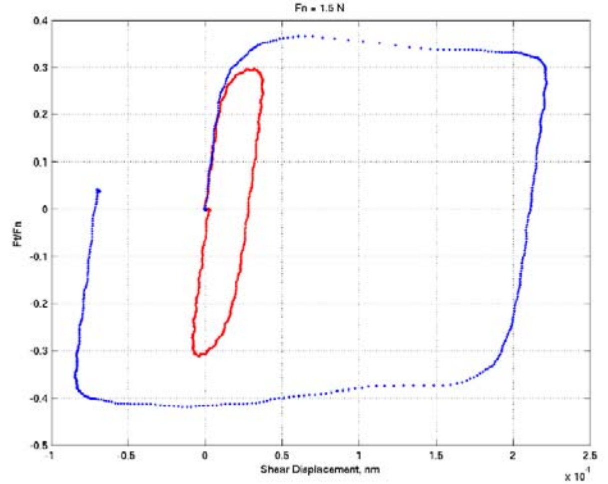
normal load, $F^* = \mu P$
sliding sphere, $\gamma = 2/3$
coefficient of friction μ,



Early data showing good resolution and repeatability



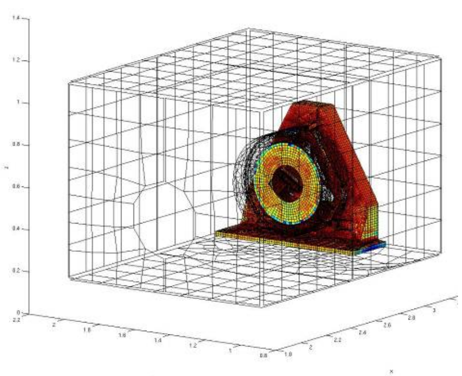
Example of gross slip



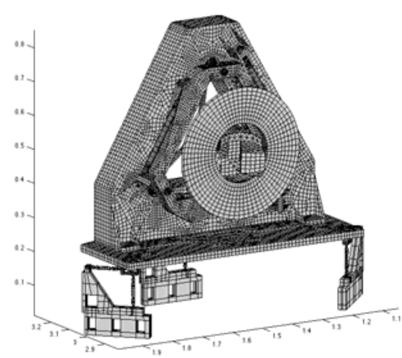
Example: SIM TOM-3 Testbed Validation

Thermo-Opto-Mechanical testbed for SIM
Measure thermally induced optical deformations of a full-size flight-like beam compressor and siderostat in flight like thermal environments

Siderostat mirror with double cube-corner including cans, yoke, and blankets



Box, Cans, Siderostat



Siderostat

Common high fidelity model with thermal, structural and optical attributes

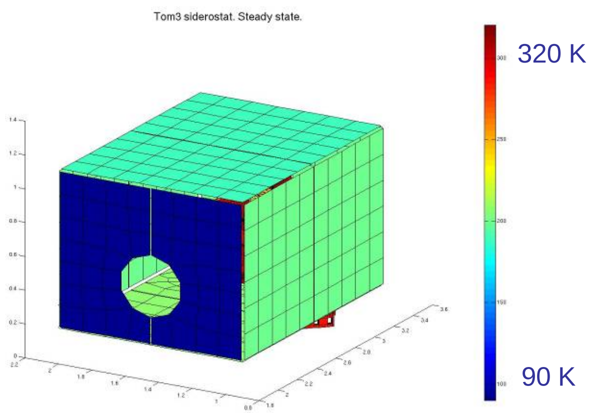
- Thermal radiation surface properties, conduction and capacitance
- Structural stiffness, thermal expansion
- Optical elements for aberration

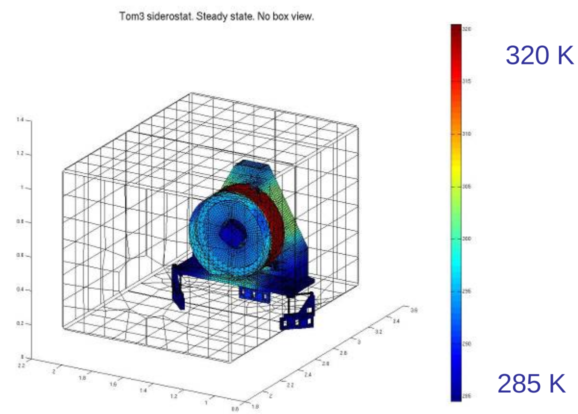
Example: SIM TOM-3 Testbed Validation (cont.)

Test/analysis correlation of:

- Steady state and transient temperatures
- Thermal deformations
- Optical aberrations (optical path differences) have been compared

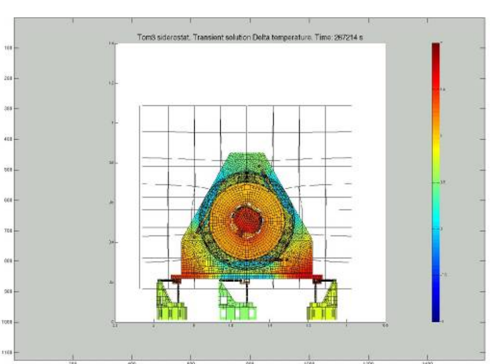
Steady state temperatures



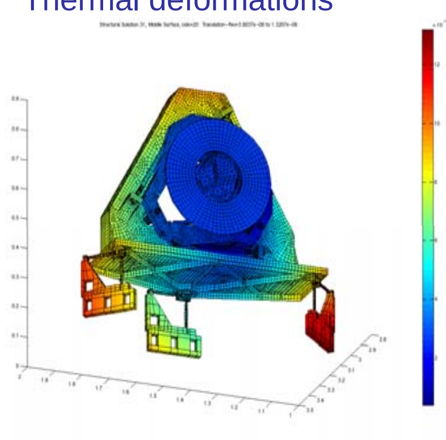


Cielo agrees well with results from COTS (TMG for thermal, NX/Nastran for structural, in-house tools for optical) and with measured results from the testbed

Transient temperatures



Thermal deformations



Optical aberrations