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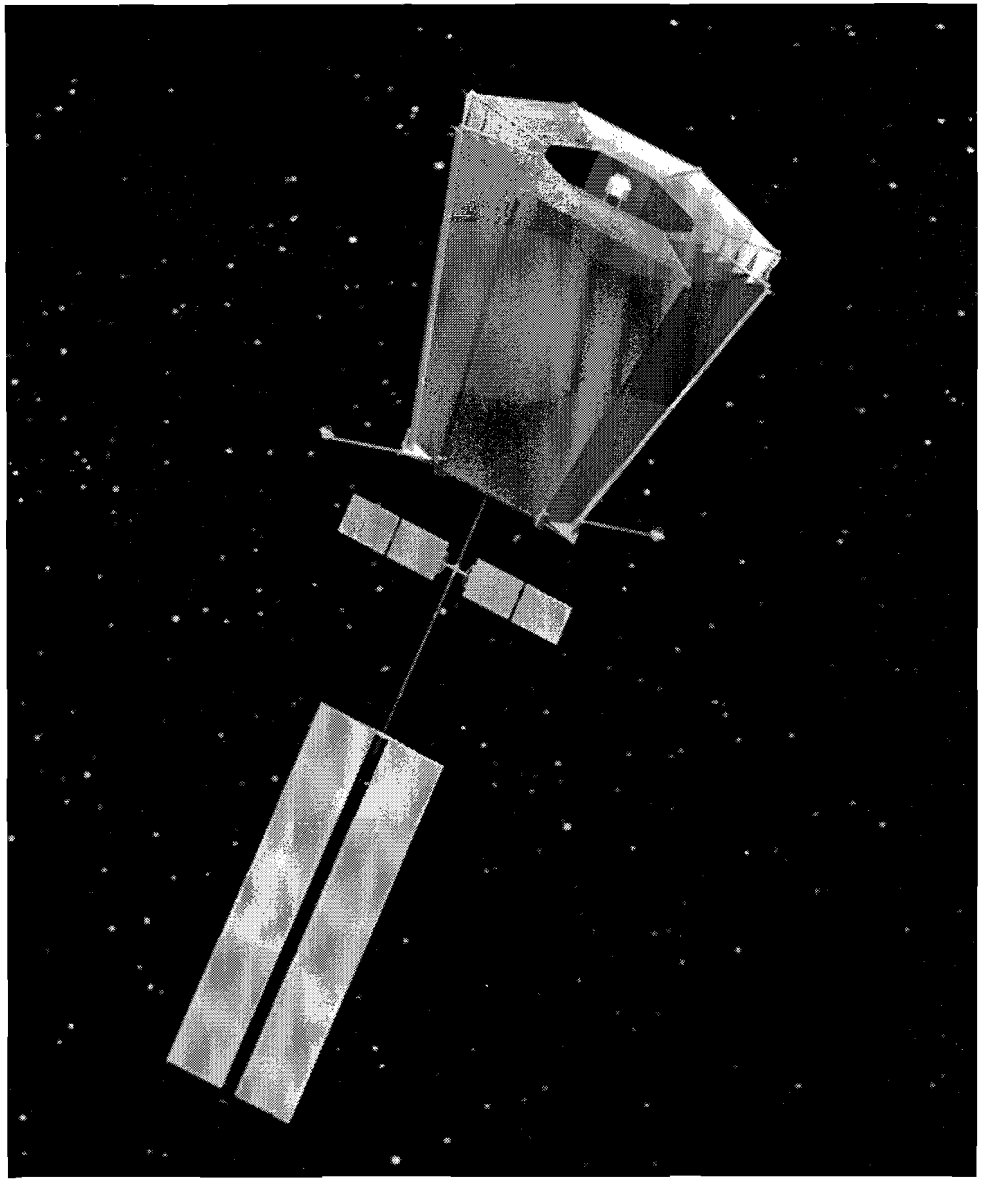
Jet Propulsion Laboratory
California Institute of Technology

Terrestrial Planet Finder Coronagraph and Enabling Technologies

Virginia G. Ford
TPF-Coronagraph System Manager

REPRESENTING WORK OF TPF CORONAGRAPH TEAM

NORTHROP GRUMMAN Space Technology
Ball Aerospace & Technologies Corp.
LOCKHEED MARTIN
TC Technology
Goddard Space Flight Center
MIDE



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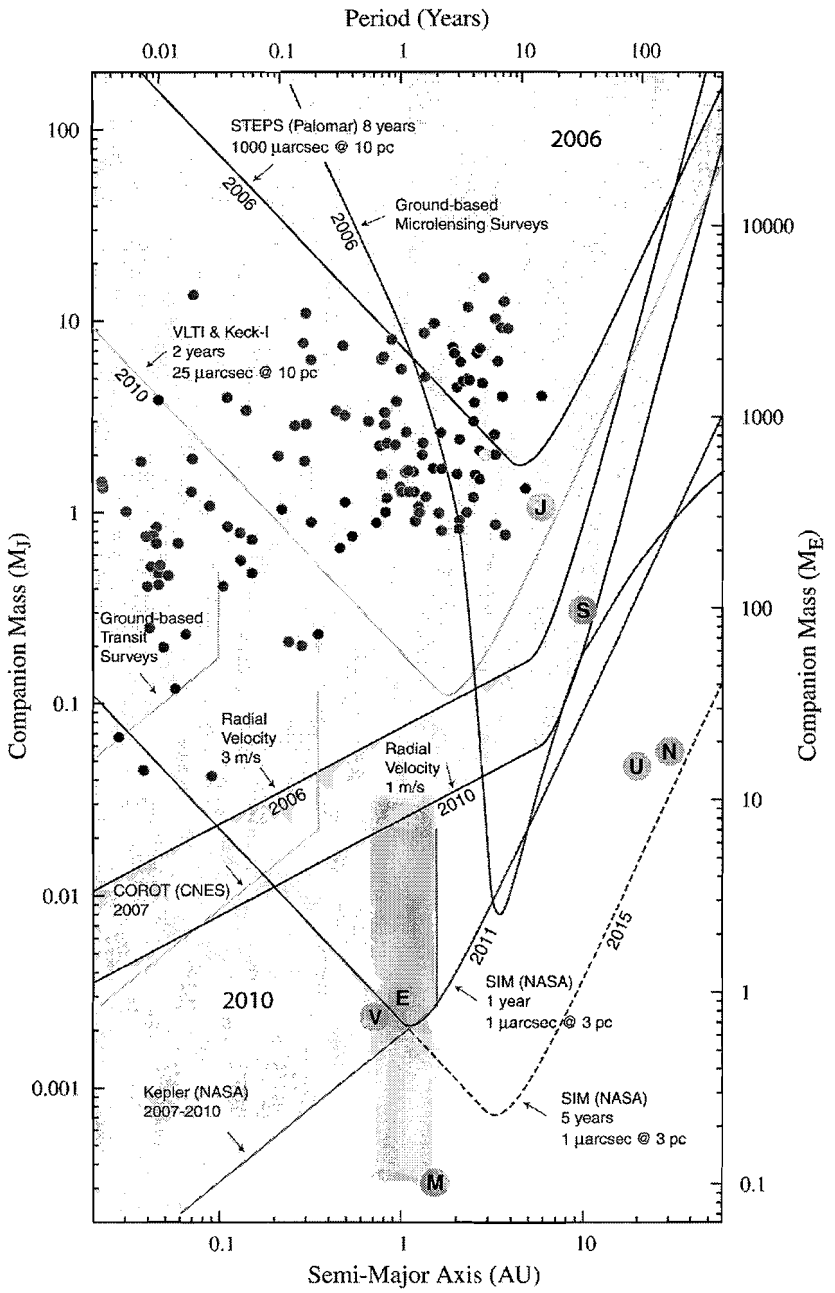
Searching for Extra-Solar Planets

- Since the mid 1980s dust disks around distant stars have been observed. Swirls and clear features in the observed disks indicate the presence of planets.
- New Neptune-mass planets reported, 31 August 2004.
  - GJ 436 b (Butler et al) 0.067 Mj
  - 55 Cnc e (McArthur et al) 0.045 Mj
  - HD 160691 d (Santos et al) 14 Me
- Spitzer observations of Exozodiacal dust (*Astrophysical Journal,.* in press)
  - 266 nearby stars surveyed
  - 71 found to harbor disks
- Planets detected through August 2004
  - Blue dots show R-V detections
  - Red dots show transit detections
  - Yellow dot shows microlensing detection



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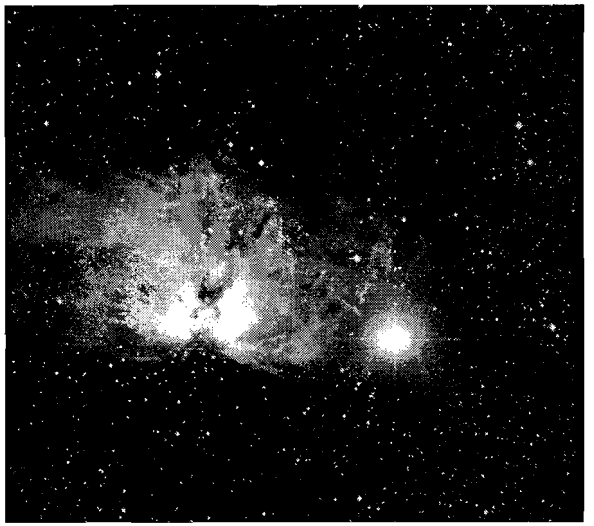
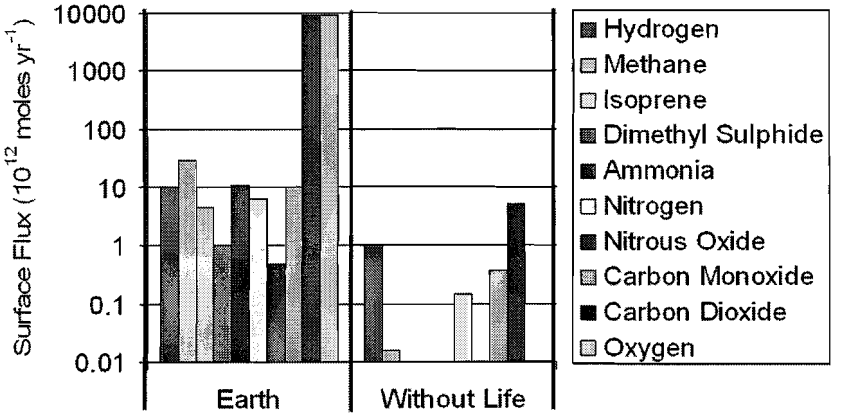
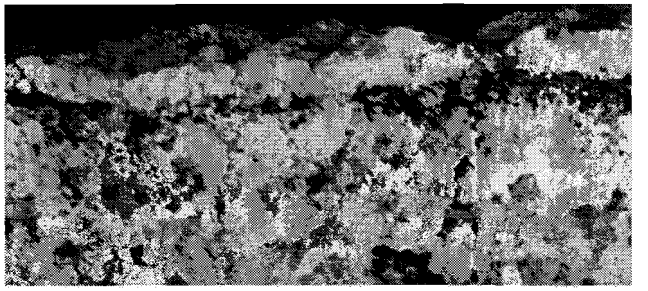
Four Fundamental Facts About the Search for Planets and Life



1. Planets are a common outcome of star formation
   - Modern theory of *star* formation makes *planet* formation likely
2. The necessary ingredients of life are widespread
   - Observation reveals uniformity of physical and chemical laws
   - Origin of the elements and their dispersal is well understood
   - Carbon bond is unique and ubiquitous! Forget Silicon life.
3. Life affects a planet in a detectable way
   - Our own atmosphere reflects the presence of life
4. Life is Hardy
   - Extremophiles can live in hot (~120 C) acid lakes, near undersea volcanic vents, in underground aquifers, and within rocks in Antarctica
   - Life needs water, a source of energy, and cosmically abundant elements





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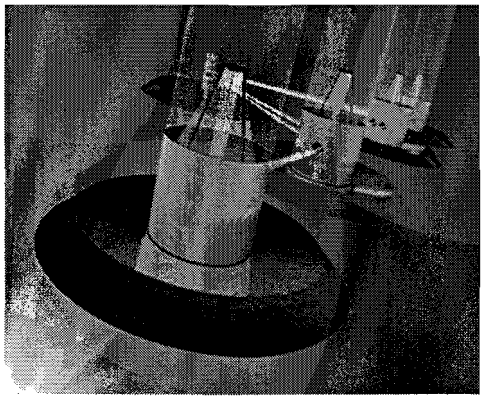
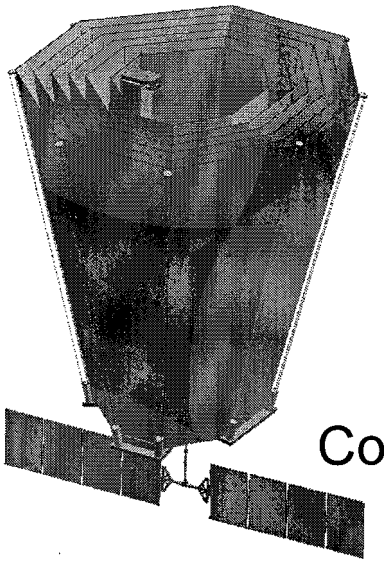
NASA-sponsored Terrestrial Planet Finder (TPF) Program at JPL

MISSION – TWO PARTS

- Search 30 to 150 nearby stars and detect planets in the habitable zone
  - Habitable zone (where liquid water can exist)
  - Defined for each star by its brightness
- Spectrally characterize the atmosphere to determine if any are terrestrial planets



Formation Flying IR Interferometers

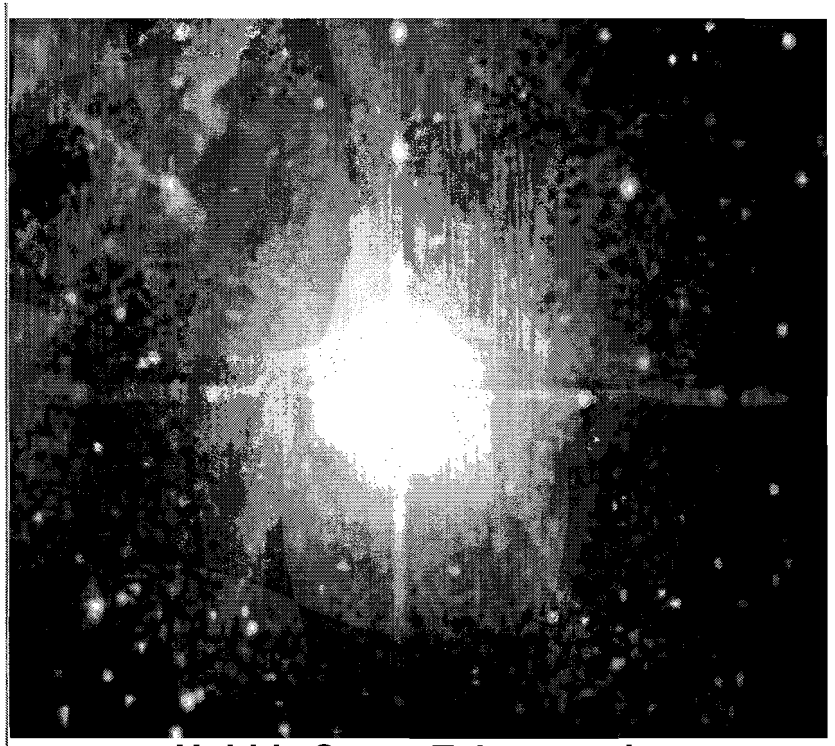


Visible Coronagraphs (my system)

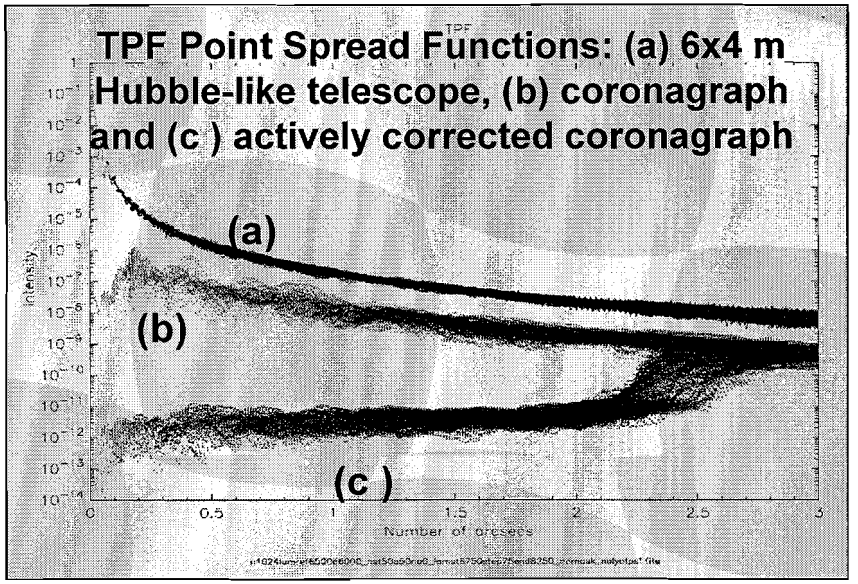
PROGRAM STRUCTURE

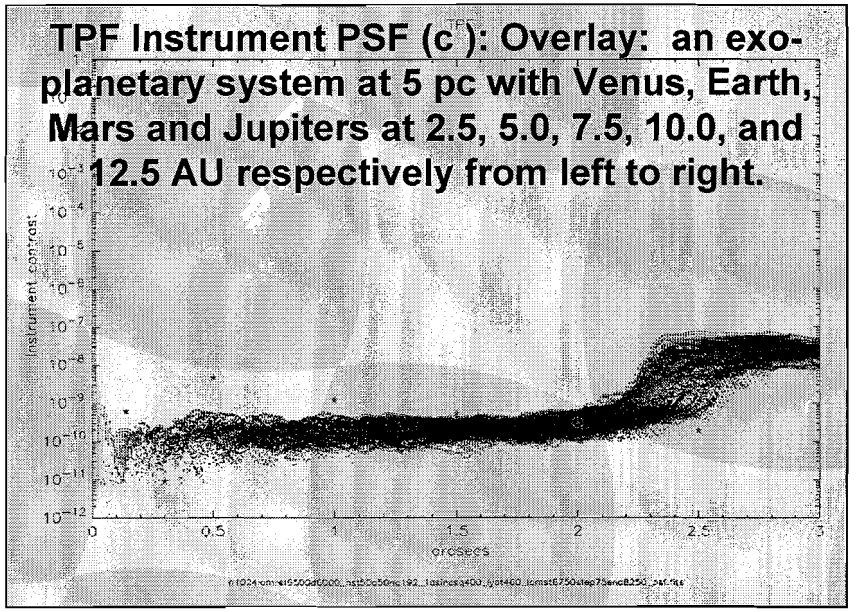
- Two teams developing two types of instruments
- Coronagraph to fly around 2014, Interferometer to fly around 2018
- Both wavelength bands needed to discern life-bearing atmospheres (prevent false positives)

Theoretical Point Spread Function vs Radius



Hubble Space Telescope Image





- Specially designed telescope required
  - Optimized to reduce diffraction speckle
- Wave Front Sensing and Control to correct wavefront errors

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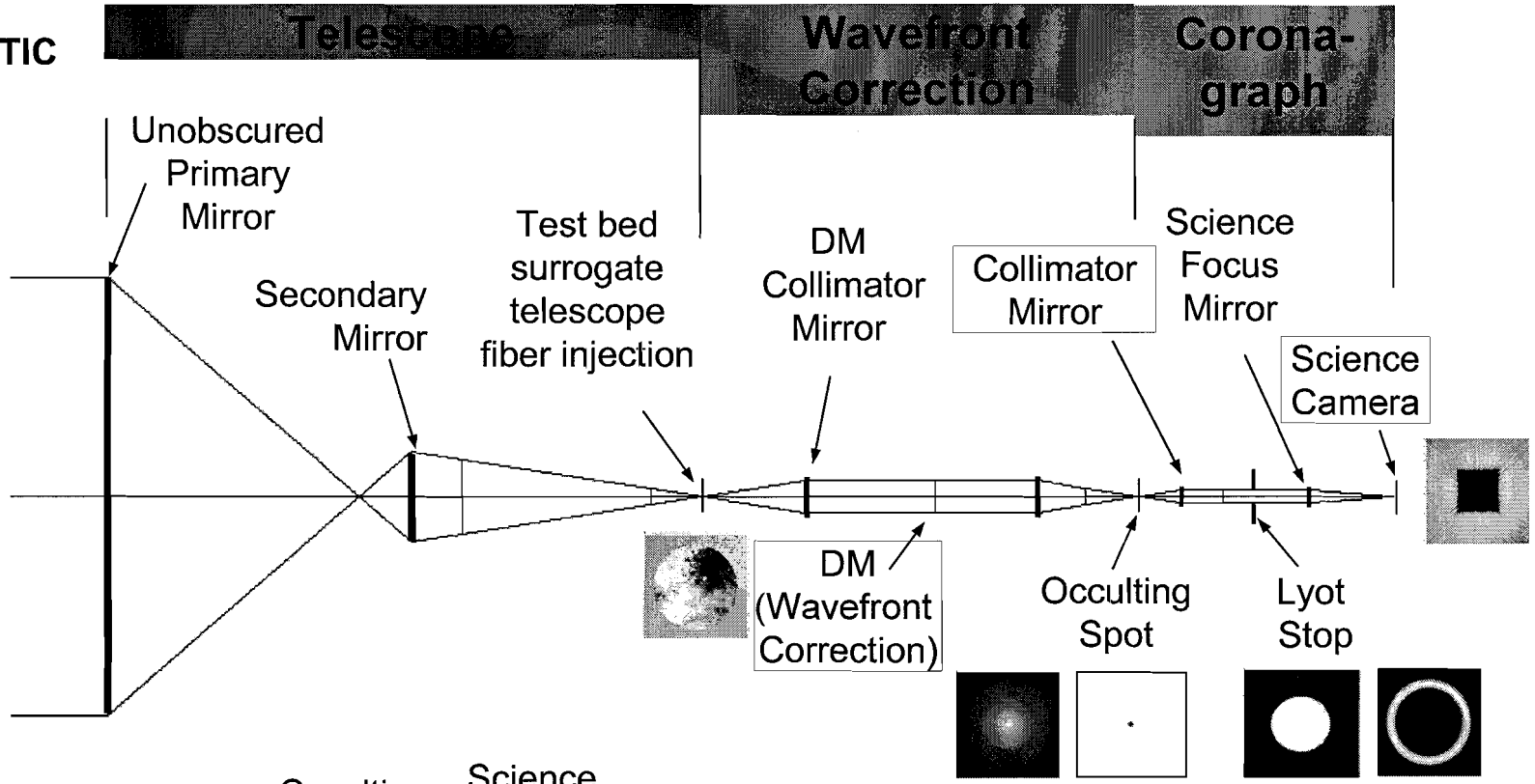
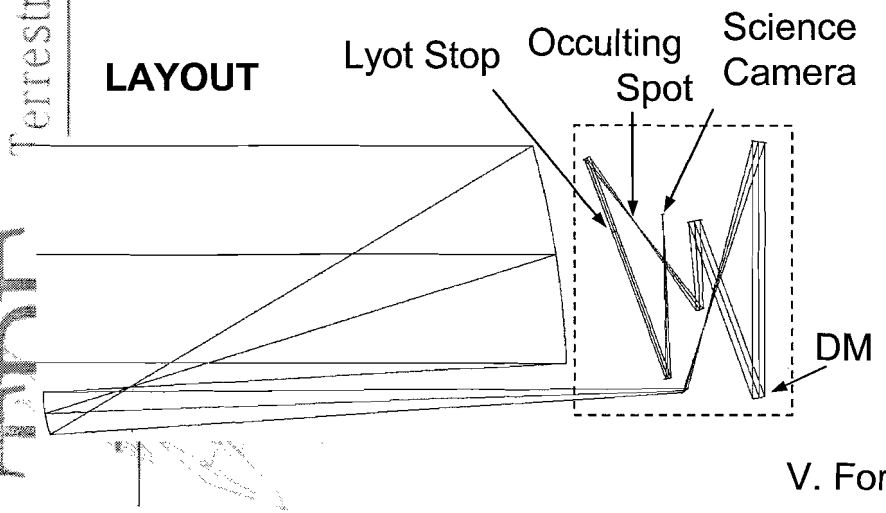
TPF Coronagraph Description - Optics

Terrestrial Planet Finder

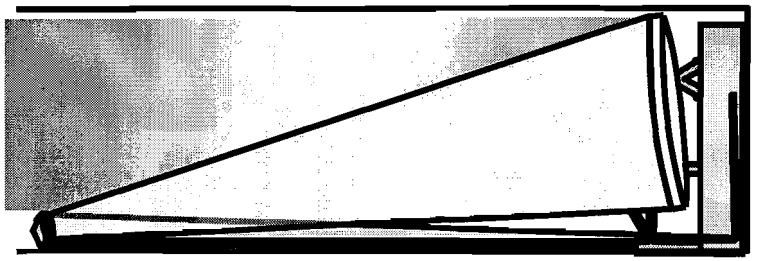
SCHEMATIC



LAYOUT



TELESCOPE



Two-fold Approach – Technology demonstration – Develop & analyze an architecture

Technology Demonstration

Current Activities

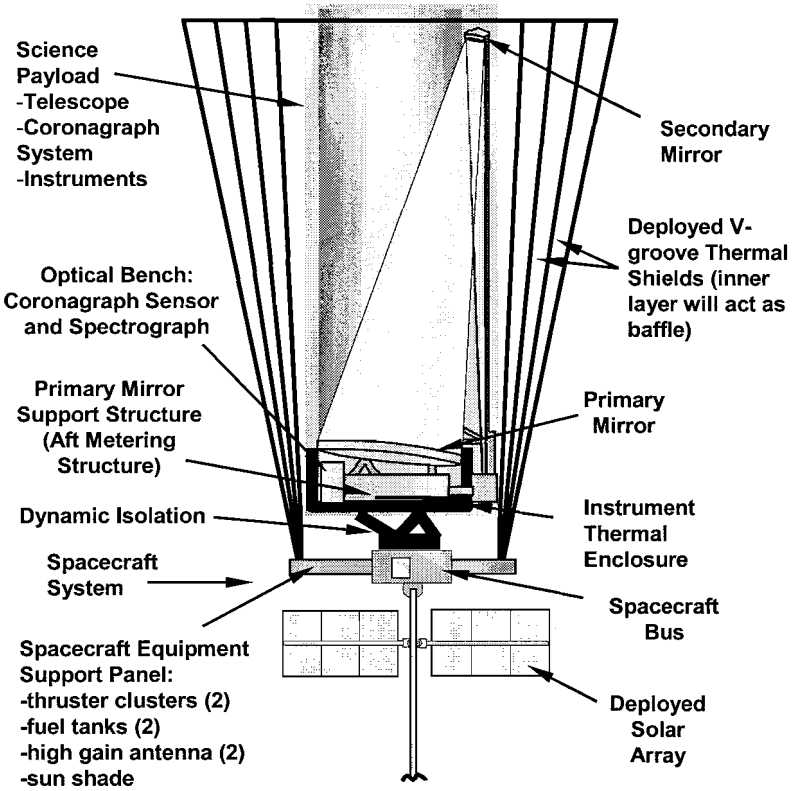
- Starlight suppression
- Wave Front Sensing and Control
- Masks and Stops development
- Large lightweight mirror development
- Coating design and analysis
- Picometer measurement of materials properties
- Modeling tool development that includes diffraction, polarization and precision that is required

Additional Activities

- Laser Metrology – leverage off of technology development from SIM and LISA
- Additional material properties measurements – leverage off of SIM testbeds
- Test and characterize structural microdynamic stability – leverage off of TPF-I studies
- Active Damping techniques – industry contribution

Architecture Development

schematic



- **View 35 close stars**
- **Work at Inner Working Angle = 3λ/D**
- **Wavelength range: 500-800 nm**
- **First cut design based on Ball Aerospace Corp. study**

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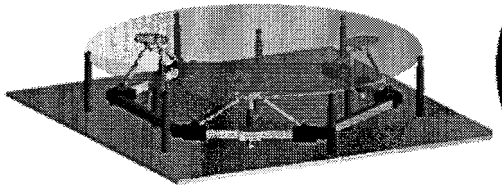
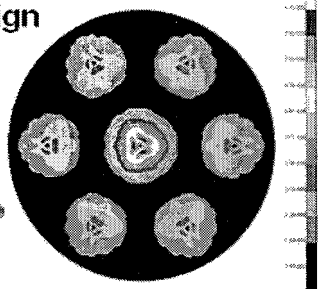
Technology Development

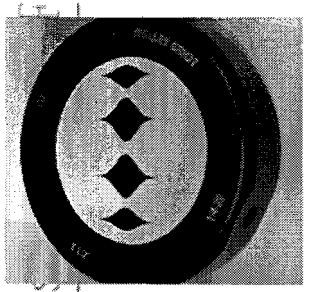
Risk reduction advanced concepts: Visible Nuller, Phase Mapping

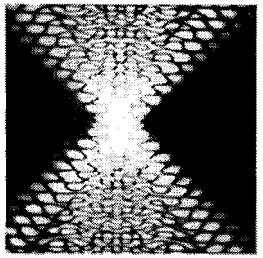
Kodak Technology Demonstration Mirror design and analysis



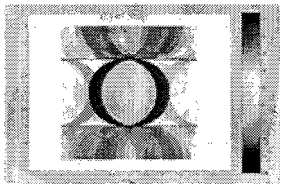


Mask Design and Analysis – TPF funded research at JPL, Berkeley, Ball Aerospace, GSFC and Princeton

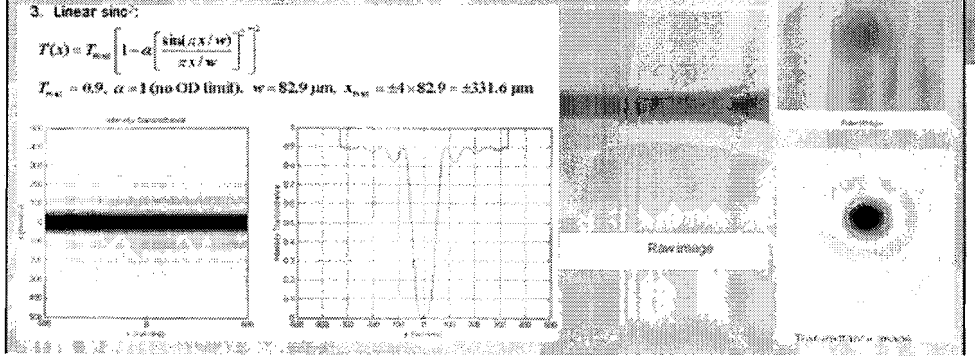




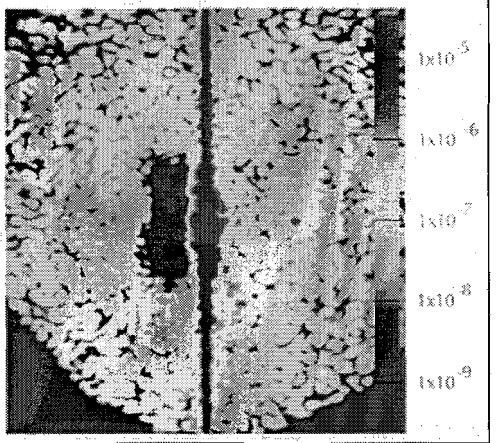
Binary Mask Performance, Including Approximate Full-Wave effects



HEBS Glass Mask Design/Fabrication



HCIT Contrast



Data by Trauger, Burrows & Moody, HCIT May 2004

Mask Characterization Test Set

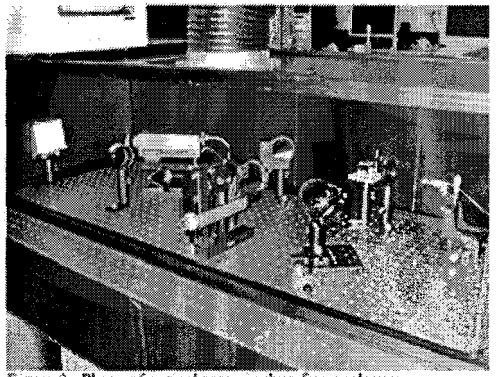
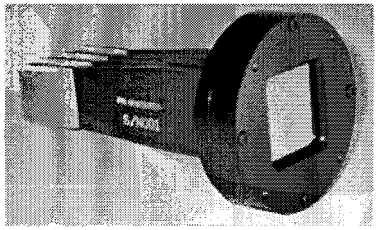
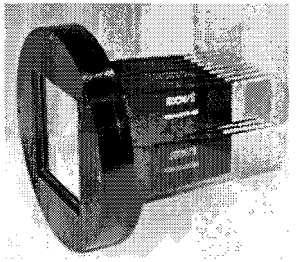
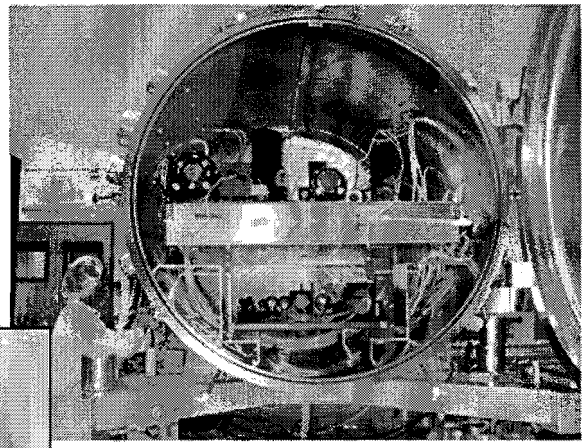


Figure 3. Photo of optical setup in dust-free enclosure.





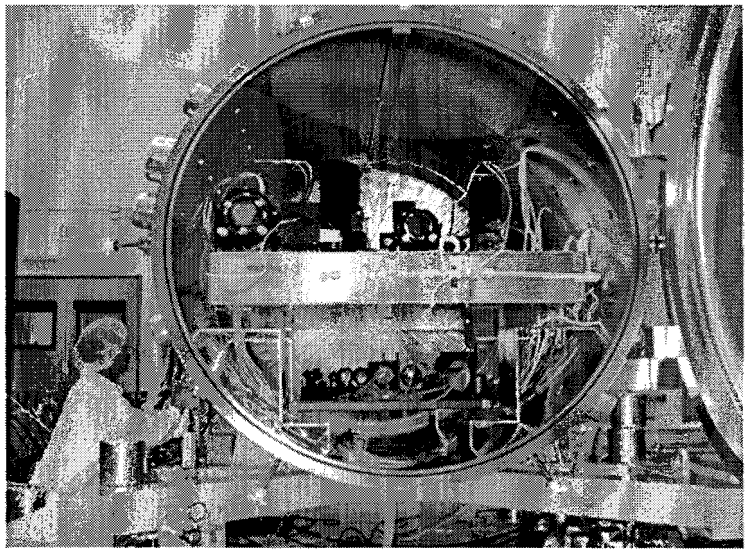


High Contrast Imaging Testbed Remote Guest Testing in progress Contrast Results to date: 1.5x10e-9

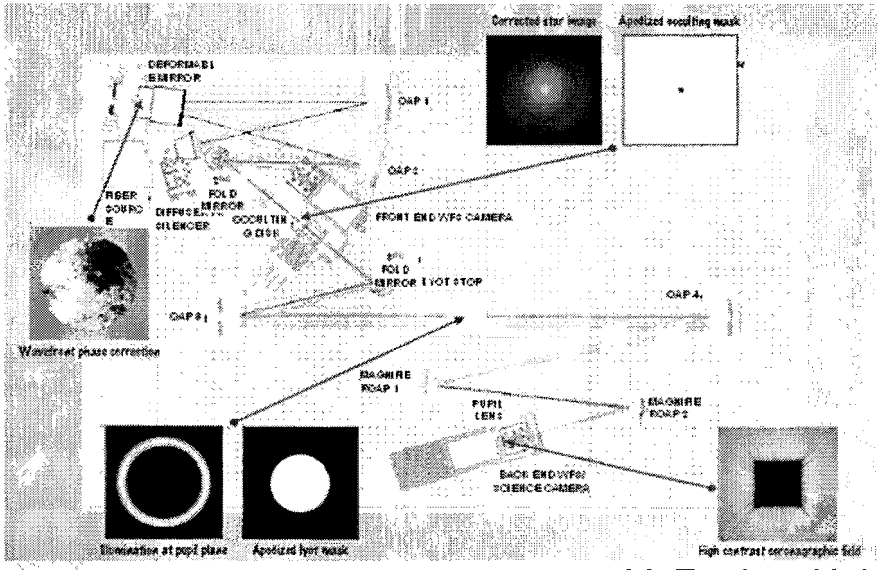
High Contrast Enabling Technology
Xinetics, Inc. Deformable Mirrors
in use in HCIT
Top: 64x64 actuator model
Bottom: 32x32 actuator model

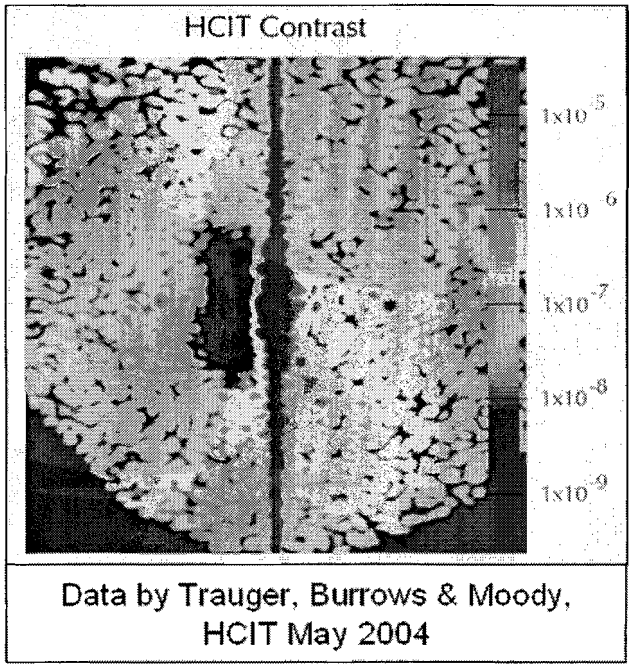
University of Florida

Technology Development



High Contrast Imaging Testbed
Remote Guest Testing in progress Contrast
Results to date: 1.5x10e-9





Data by Trauger, Burrows & Moody, HCIT May 2004

-70 nm waveband results – $5x10^{e-9}$
- Working on stability, polarization, broadening waveband
-New polarization monitoring equipment
-Binary to HEBS mask comparison measurements

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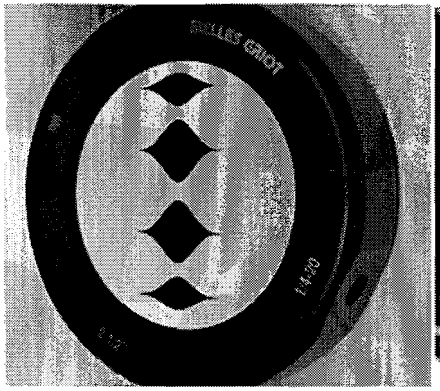
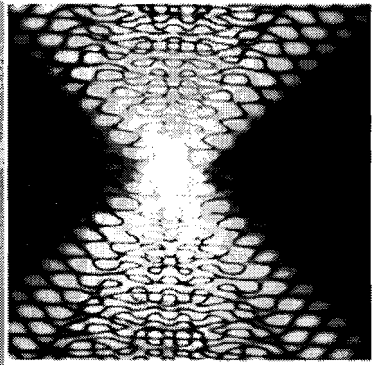
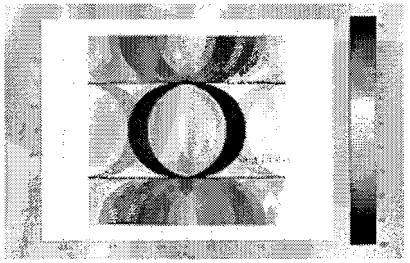
Technology Development

Mask Design and Analysis – TPF funded research at JPL, Berkeley, Ball Aerospace, GSFC and Princeton





Binary Mask Performance, Including Approximate Full-Wave effects



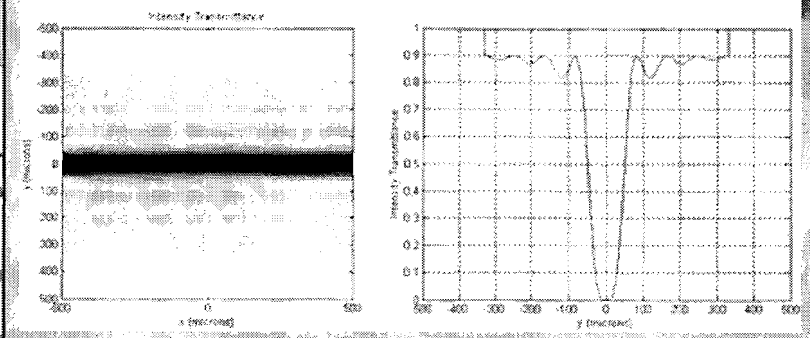
To date in Testbed – HEBS glass masks are most successful but limited

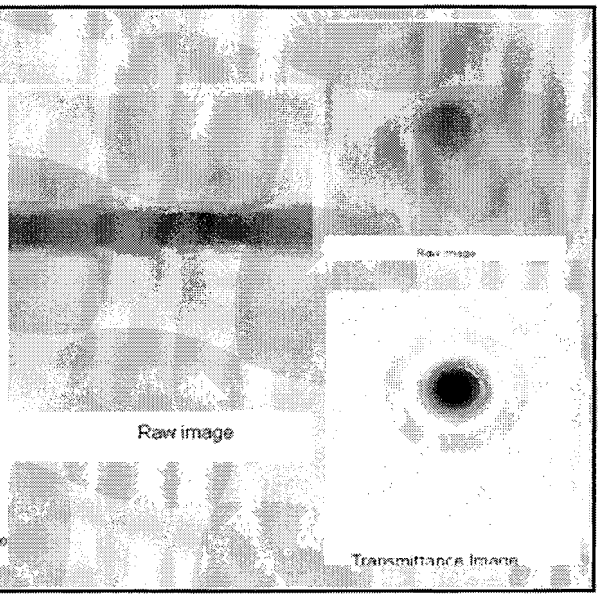
HEBS Glass Mask Design/Fabrication

3. Linear sinc²:

$$T(x) = T_{max}\left[1-\alpha\left[\frac{\sin(\pi x/w)}{\pi x/w}\right]^2\right]^2$$

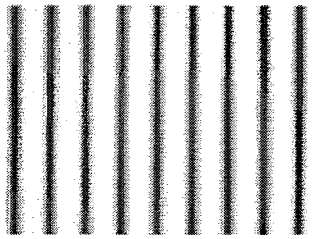
$T_{max} = 0.9$, $\alpha = 1$ (no OD limit), $w = 82.9\ \mu m$, $x_{max} = \pm 4 \times 82.9 = \pm 331.6\ \mu m$



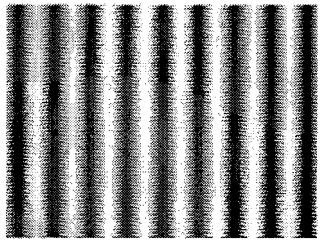


Sampled Sin² mask

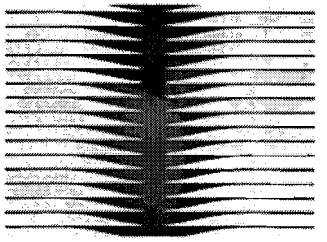
Sampled Sin² mask



Continuous Sin² mask



1-Sinc² mask



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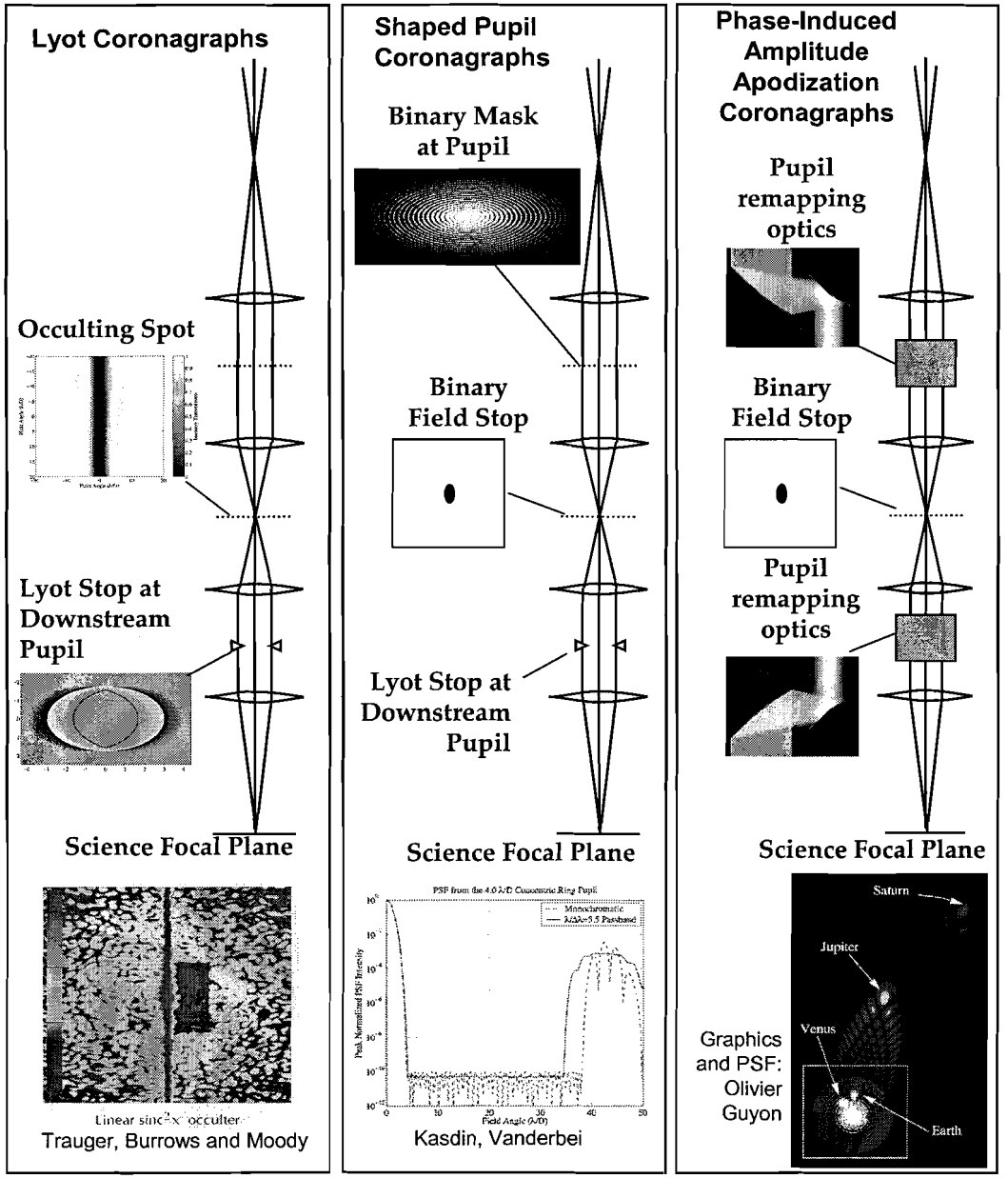
Comparison of Coronagraph Anatomies

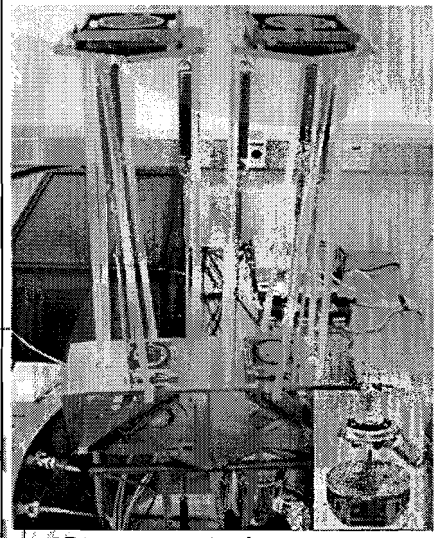
- Starlight suppression systems have different characteristics that affect sensitivities
- New types of masks and systems are being designed and built to optimize for insensitivity to chromaticity, polarization, optical component motions



Developing Technologies

Active Dynamics Damping

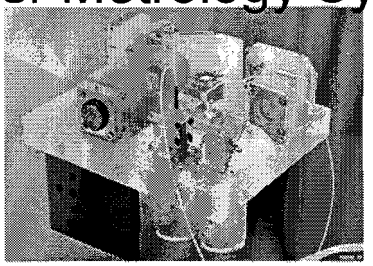
- Primary source of vibration during observation: Reaction Wheel Assembly (RWA)
- Used commercial RWA vibrations as inputs with Hubble passive damping parameters for models
- Active damping based on Lockheed Disturbance Free Payload system values



JPL Cryo Dilatometer

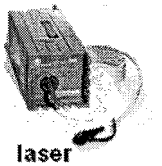
Develop data-base of extremely precise materials properties
- Some measurement in work
- More needed
- Additionally will use data collected by other projects

Laser Metrology System



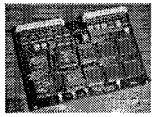
Beam Launcher

Pre-amp



laser

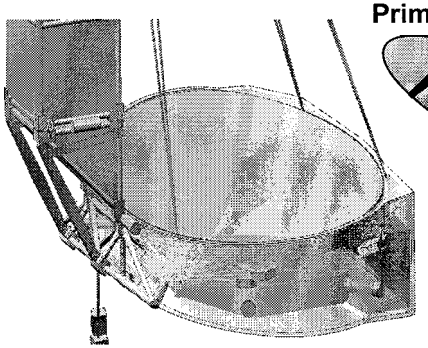
Post-amp

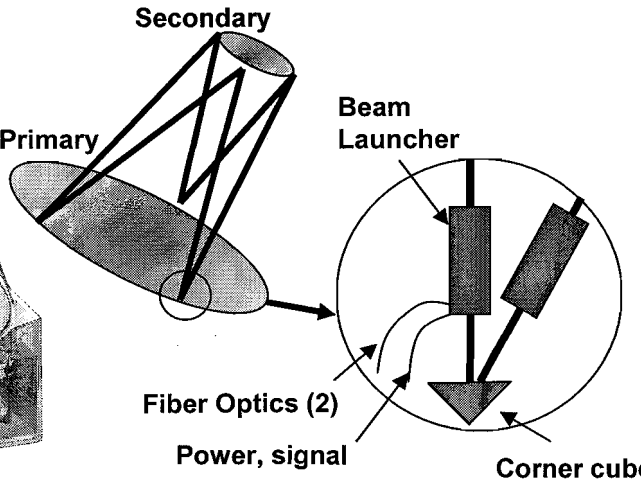


Phase meter card

Optical metrology based on SIM and LISA Technology
- Sub nanometer measurements
- 6-DOFmeasurement Primary-Secondary positions

- **Allocated tolerances:** ~1 nm z, 8 nm x&y, 5 nr θ_x& θ_y
- **SIM Metrology can meet TPF-C requirements but laser frequency stability needs to be improved**
- **LISA laser stability meets TPF-C requirements, but may need different wavelength**





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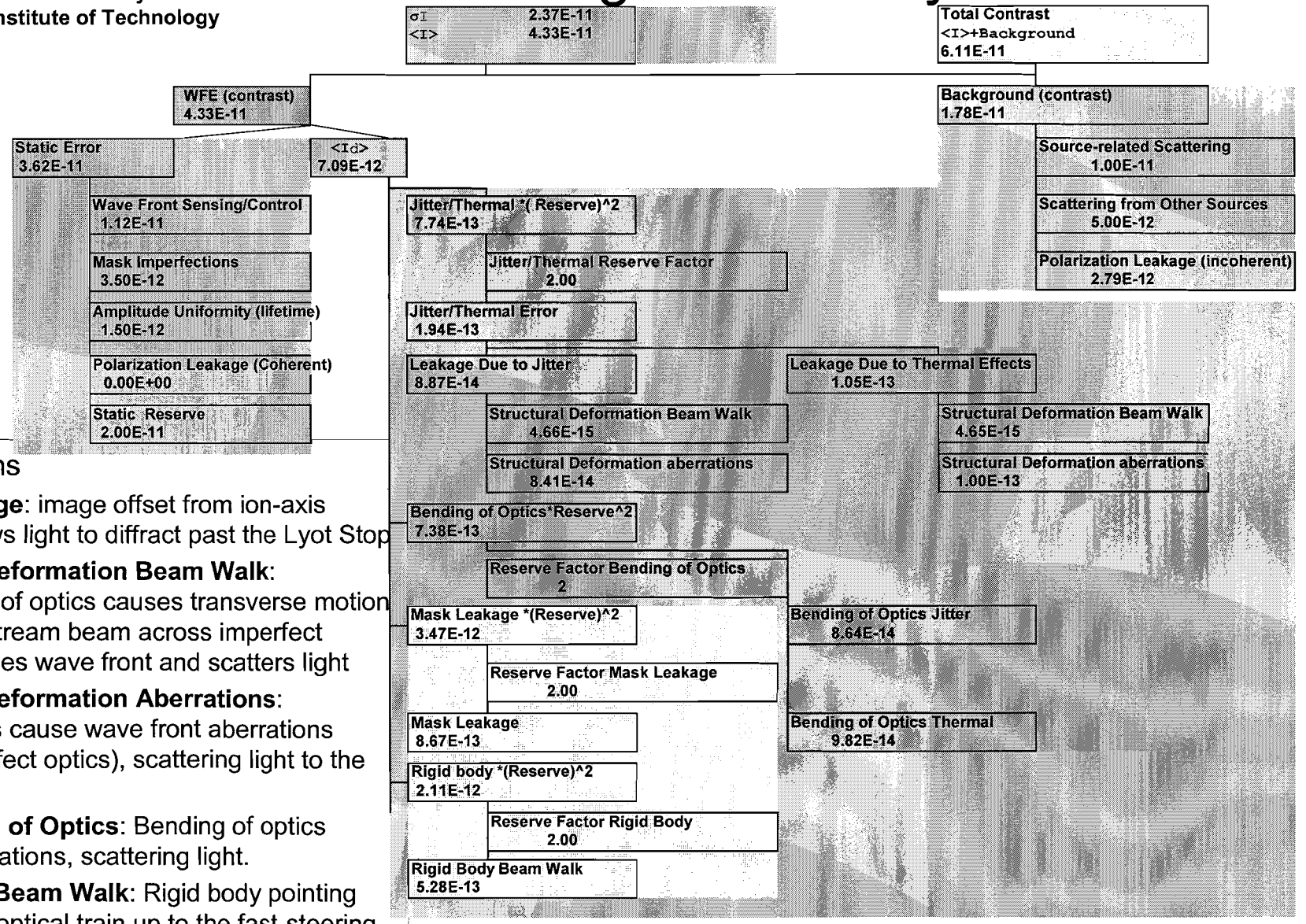
Error Budget Summary



Error Tree Terms

- **Mask Leakage**: image offset from ion-axis position allows light to diffract past the Lyot Stop
- **Structural Deformation Beam Walk**: Tip/tilt/piston of optics causes transverse motion of the downstream beam across imperfect optics -modifies wave front and scatters light
- **Structural Deformation Aberrations**: Perturbations cause wave front aberrations (even for perfect optics), scattering light to the image plane
- **Deformation of Optics**: Bending of optics causes aberrations, scattering light.
- **Rigid Body Beam Walk**: Rigid body pointing errors of the optical train up to the fast-steering mirror result in transverse beam motion.

Error Budget values

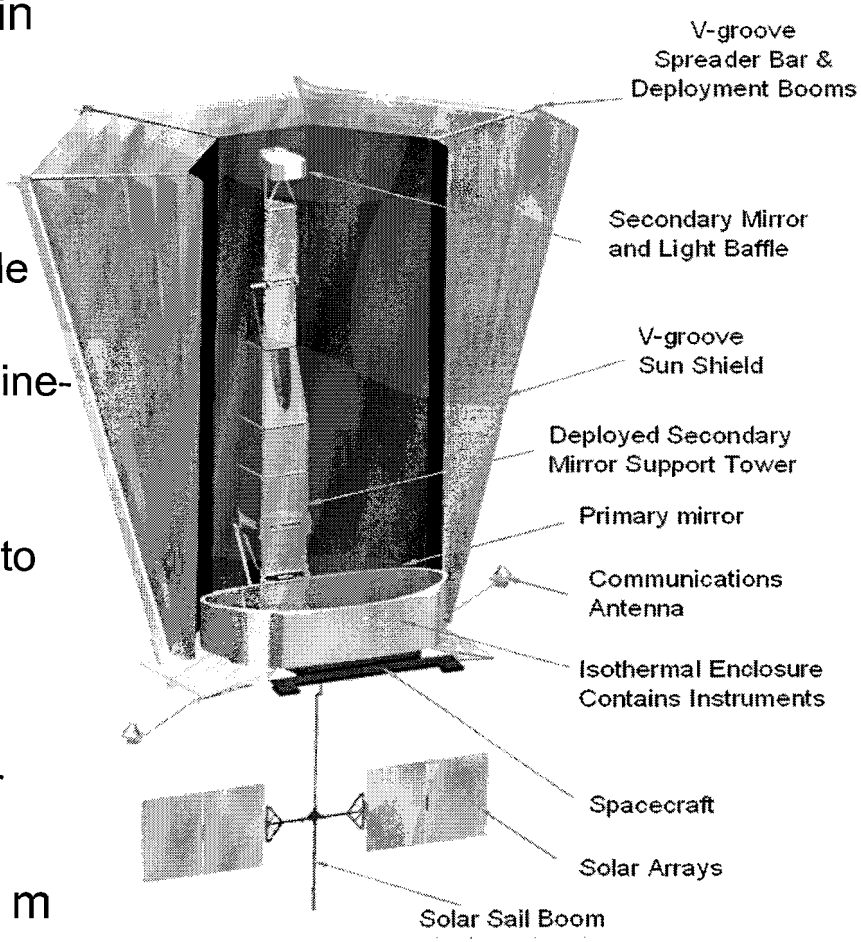
Deformation of Optics (Thermal)					
zernike mode	Primary rms amp(Å)	Sec rms amp(Å)	Sf rms amp(Å)	Sp rms amp(Å)	Dm rms amp(Å)
4	0.022857	0.005714	0.002857	0.002857	0.002857
5	0.014286	0.003571	0.001786	0.001786	0.001786
6	0.014286	0.003571	0.001786	0.001786	0.001786
7	0.002857	0.000714	0.000357	0.000357	0.000357
8	0.002857	0.000714	0.000357	0.000357	0.000357
9	0.002857	0.000714	0.000357	0.000357	0.000357
10	0.002857	0.000714	0.000357	0.000357	0.000357
11	0.001429	0.000357	0.000179	0.000179	0.000179
12	0.002857	0.000714	0.000357	0.000357	0.000357
13	0.002857	0.000714	0.000357	0.000357	0.000357
14	0.002857	0.000714	0.000357	0.000357	0.000357
15	0.002857	0.000714	0.000357	0.000357	0.000357

Motions utilized for jitter and aberration sensitivity This is for all elements except Primary and Secondary		
	Tilt (nrad)	Translation (nm)
Fold1	5.00	5.00
Fold2	5.00	5.00
DM OAP1	5.00	5.00
Pol-BS1	5.00	5.00
Pol-BS2	5.00	5.00
Fold3	5.00	5.00
Michelson BS	5.00	5.00
Wedge 1	5.00	5.00
DM	5.00	5.00
Fold4	5.00	5.00
Relay OAP2	5.00	5.00
Relay OAP3	5.00	5.00
Reflector (OAP4)	5.00	5.00
Reflector Flat	5.00	5.00
Occulting Mask Return	5.00	5.00
Exit Pupil Return	5.00	5.00

Rigid body motions				
	Tilts (nR)	Tilts(mas)		
x	4	0.8		
y	4	0.8		
z	4	0.8		
Beam Walk Contrast due to pointing (rigid body)				
Element	Dx	2l/D	3l/D	4l/D
Primary	6.29E-07	6.14E-17	4.52E-17	8.01E-17
Secondary	8.40E-09	2.29E-17	2.27E-17	2.23E-17
Fold Mirror 1	6.78E-07	6.56E-14	6.84E-14	6.17E-14
Fold Mirror 2	9.05E-07	1.17E-13	1.22E-13	1.10E-13
DM Collimator (O/	7.88E-07	2.90E-13	3.22E-13	2.63E-13
DM	1.72E-07	2.25E-33	1.65E-33	2.93E-33
Relay OAP2	1.97E-07	3.33E-23	3.69E-23	3.01E-23
BS1	1.50E-07	4.37E-16	4.56E-16	4.11E-16
BS1	1.43E-07	9.18E-15	9.57E-15	8.63E-15
BS1	1.61E-07	3.32E-16	3.47E-16	3.13E-16
BS2	1.21E-07	3.03E-16	3.16E-16	2.85E-16
BS2	1.09E-07	3.83E-16	3.99E-16	3.60E-16
BS2	5.27E-08	2.17E-16	2.26E-16	2.04E-16
Fold Mirror 3	4.89E-08	2.80E-15	2.92E-15	2.63E-15
Michelson BS	2.71E-08	4.09E-17	4.27E-17	3.85E-17
Michelson BS	2.04E-08	5.65E-16	5.89E-16	5.31E-16
Michelson BS	1.69E-08	1.09E-17	1.13E-17	1.02E-17
Wedge 1	3.87E-17	6.12E-18	6.38E-18	5.76E-18
Wedge 1	2.33E-13	4.21E-18	4.39E-18	3.96E-18
Wedge 1	2.81E-13	7.98E-28	8.32E-28	7.51E-28
Wedge 1	3.74E-13	1.16E-27	1.21E-27	1.09E-27
Michelson BS	6.90E-13	2.06E-27	2.15E-27	1.94E-27
Michelson BS	7.26E-13	7.02E-27	7.32E-27	6.60E-27
Michelson BS	1.80E-12	7.76E-27	8.09E-27	7.30E-27
Fold Mirror 4	7.87E-12	7.67E-25	7.99E-25	7.21E-25
Relay OAP3	6.15E-12	2.04E-23	2.26E-23	1.84E-23
Relay OAP4	6.71E-12	2.43E-23	2.69E-23	2.20E-23
Reflector Flat	2.10E-11	1.04E-22	1.08E-22	9.74E-23
Occulting Mask R	2.81E-11	1.87E-22	1.95E-22	1.76E-22
Exit Pupil Return	1.91E-13	8.59E-27	8.96E-27	8.08E-27

Analysis of Minimum Mission Concept

- Completed modeling and analysis in June
- Mission operations concept:
  1. Acquire target star
  2. Settle, observe and set Deformable Mirror, read out focal plane
  3. Dither (rotate 20 degrees around line-of-sight)
  4. Observe and read out focal plane
  5. Compare observations – subtract to eliminate speckles
  6. Rotate 70 degrees around line-of sight
  7. Repeat steps 2 – 5 to obtain other axis resolution
- Primary mirror 6 m x 3.5 m with 10 m spacing to secondary mirror
- Since then have been working toward developing flight baseline design



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Minimum Mission Concept Assemblies

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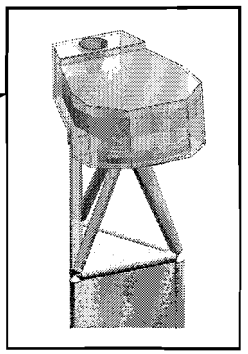
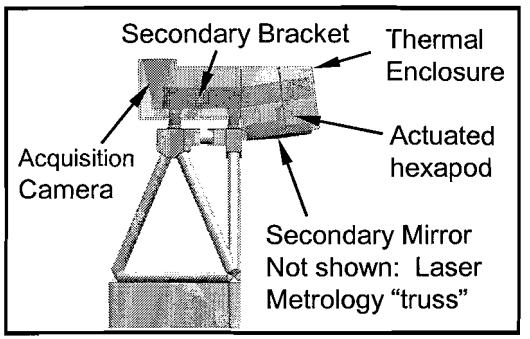
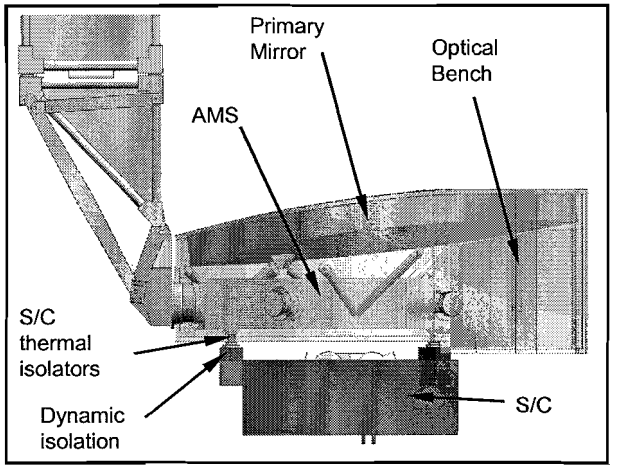
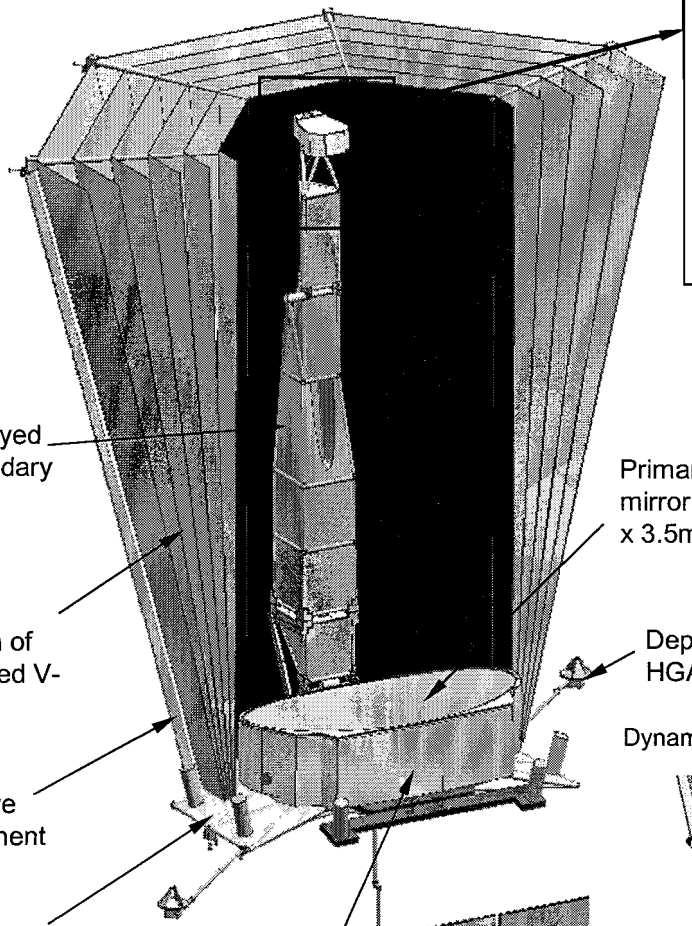
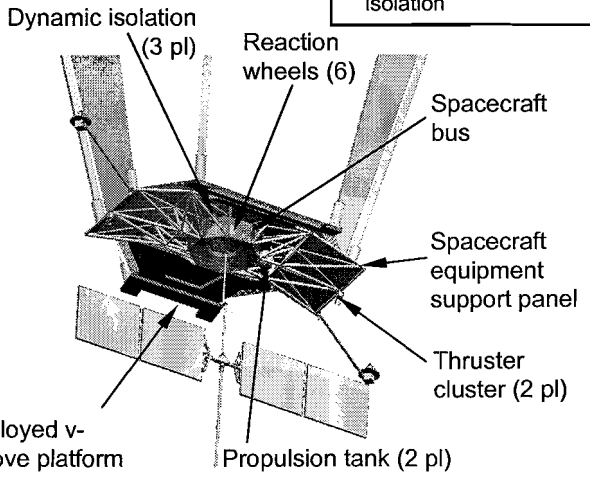
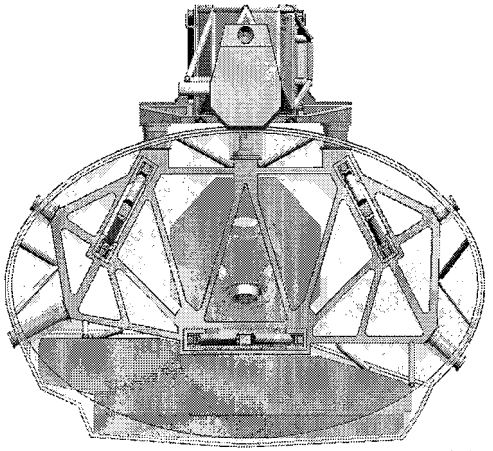




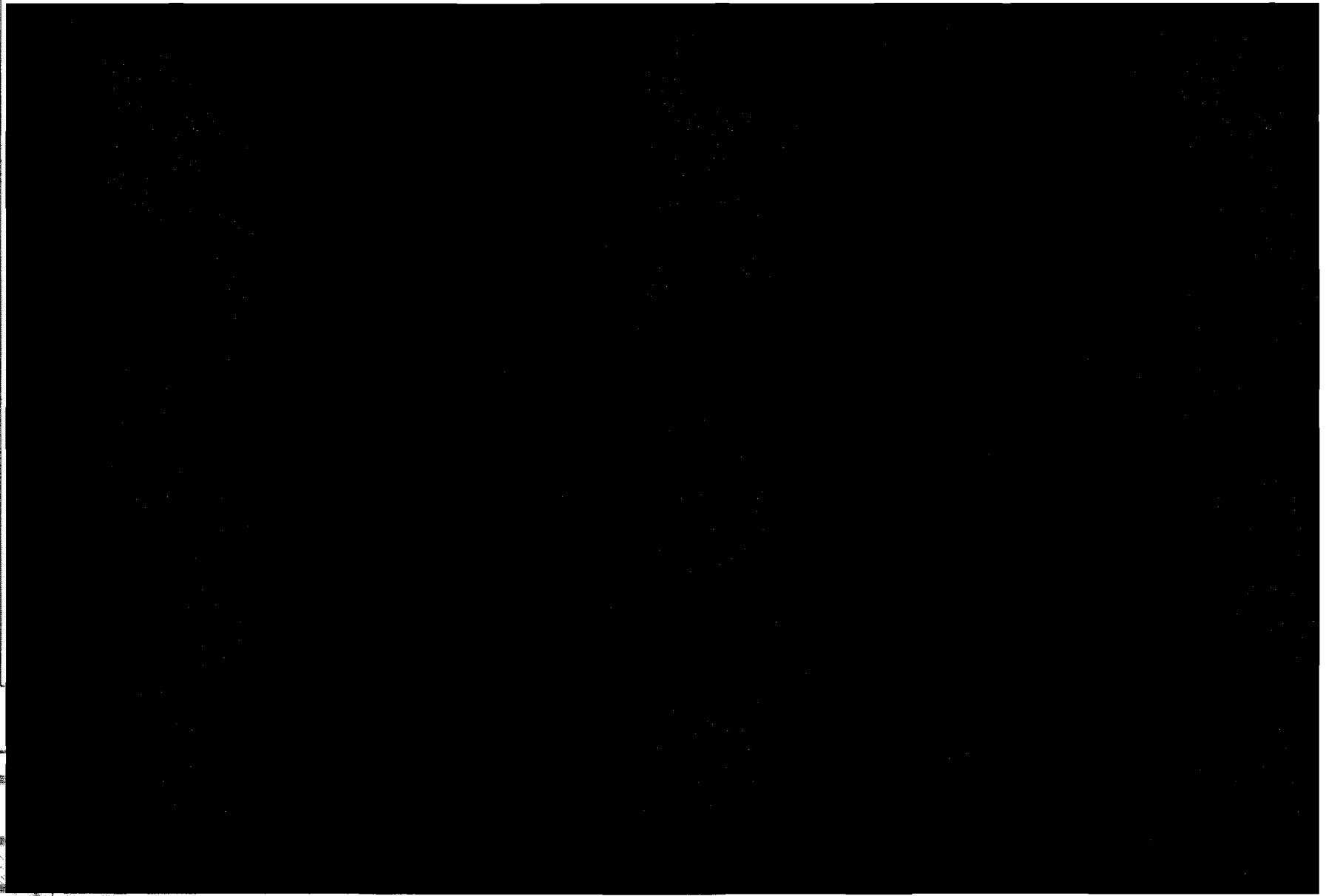








Deployment Concept



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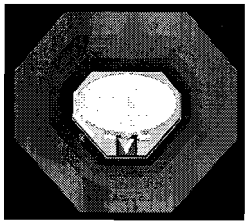
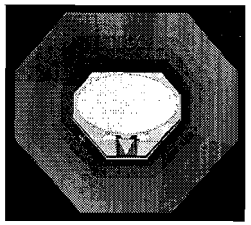
Minimum Mission Thermal Modeling

Telescope Steady-State Temperature for Two 20 deg Dither Cases (80 to 100 & 170 to 190)

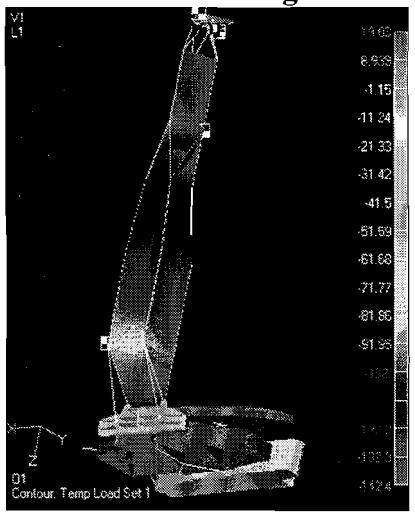
170 deg 190 deg



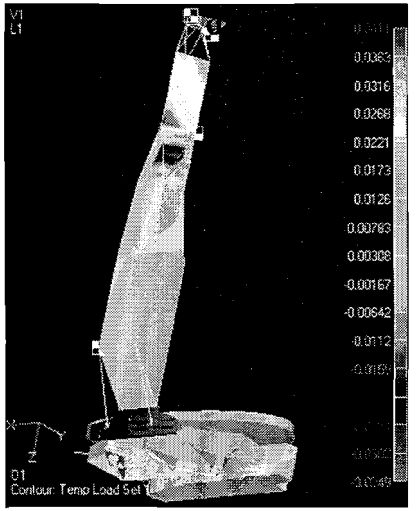
100 deg
80 deg



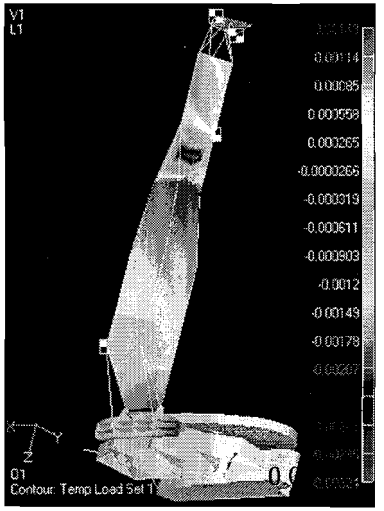
Temperature (C) Distribution for **all Sun Angles**



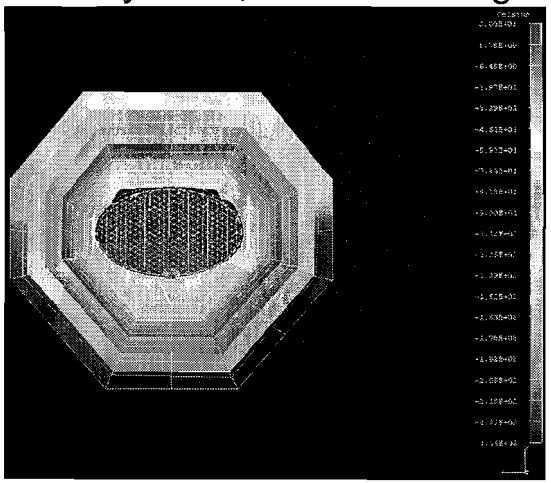
Delta Temperature (C) for Dither from **80 to 100**



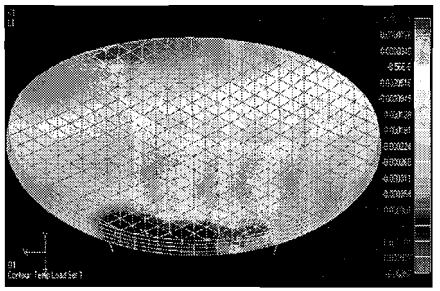
Delta Temperature (C) for Dither from **170 to 190**



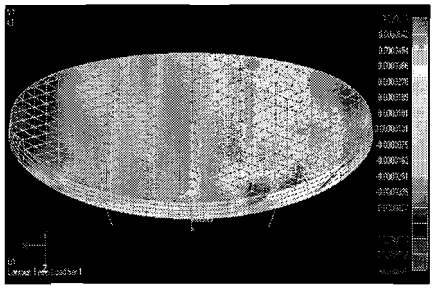
Steady State, Sun at 180 deg



Dither from **80 to 100 deg**
Front Face Sheet of PM 0.69 mK p-v



Dither from **170 to 190 deg**
Front Face Sheet of PM 0.14 mK p-v



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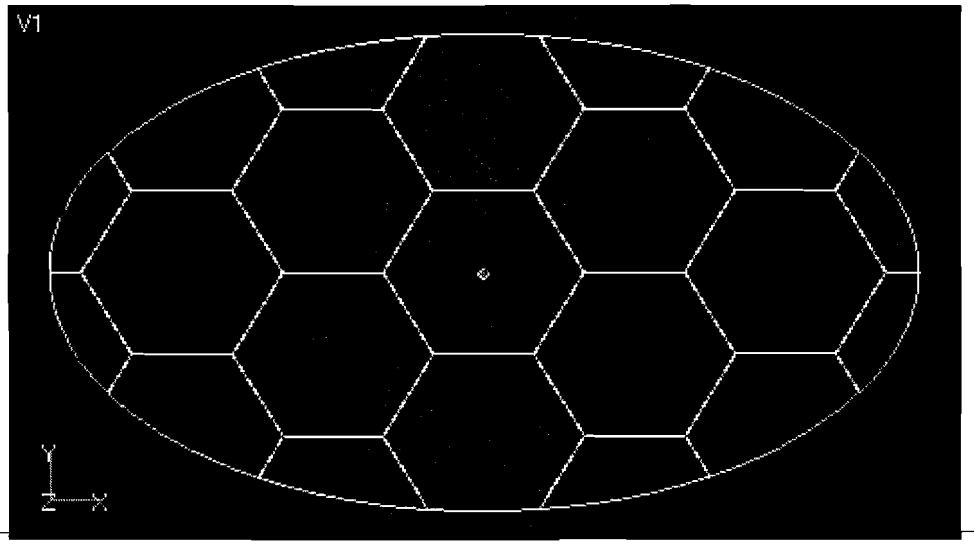
Thermal Modeling Results



Summary for PM Design with **Optimized** Segment Placement Based on 80 to 100 deg Dither

Zernike Comp	80 to 100 deg Dither Stead-State Resp (pm)	3L/D Req Specs (pm)	Ratio Req/Resp
4	0.14	2.29	16.21
7	0.19	0.29	1.47
11	0.09	0.14	1.64
12	0.11	0.29	2.53
13	0.07	0.29	3.86

Results for 170 to 190 deg Dither Using **Optimized** Segment Placement

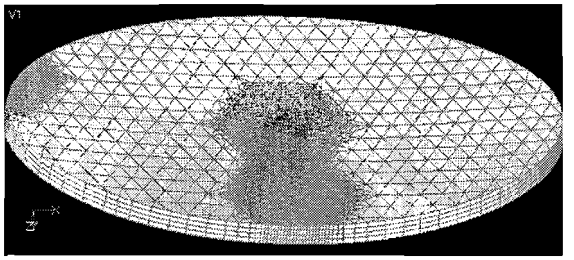
Zernike Comp	170 to 190 deg Dither Stead-State Resp (pm)	3L/D Req Specs (pm)	Ratio Req/Resp
4	0.02	2.29	126.52
7	0.06	0.29	4.88
11	0.01	0.14	22.70
12	0.01	0.29	40.28
13	0.03	0.29	9.93

Note: The results for PM with optimal segment placement are **steady-state** (conservative for dither)

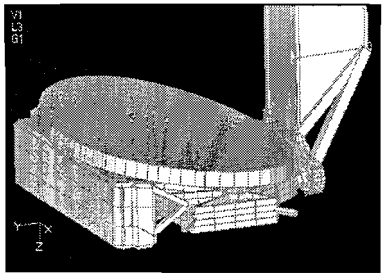
Structural and Dynamic Modeling and Analysis

Dynamic Vibration Input:

Reaction Wheel Assemblies with two layers of passive vibration isolation

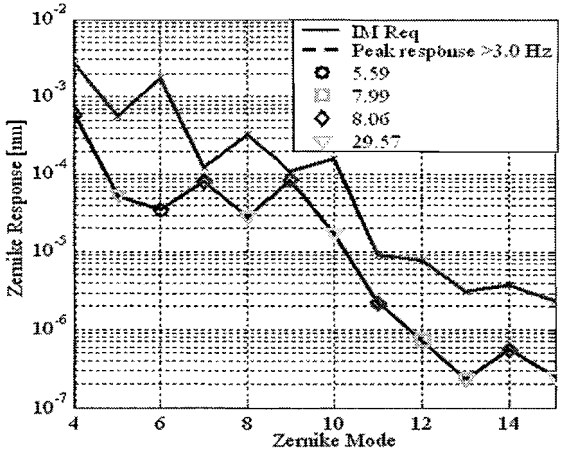


Dynamic Results - 2 stage passive isolation



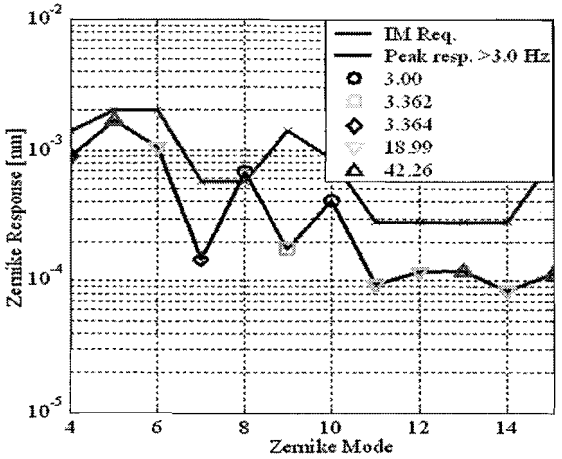
Rigid Optics Wavefront Error

Design meets requirements passively



Flexible Primary Wavefront Error

Mode 8 exceedance can be avoided by running wheels above 4hz



Materials Used:

ULE Glass (Ultra-Low Expansion Titanium Silicate Glass by Corning)

- Primary & Secondary Mirrors (good thermal stability)

K1100/954 Carbon Fiber Composite

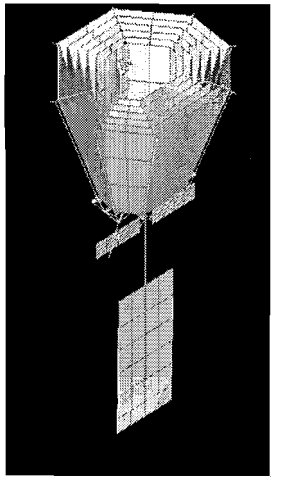
- Primary & Secondary Mirror Thermal Enclosures (high conductivity)

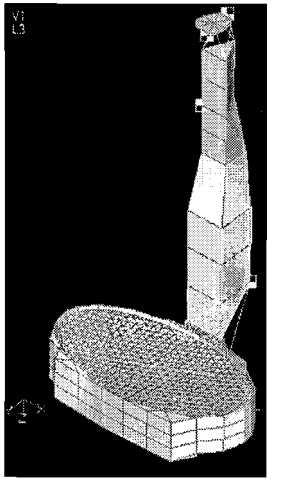
S-Glass Fiberglass Composite

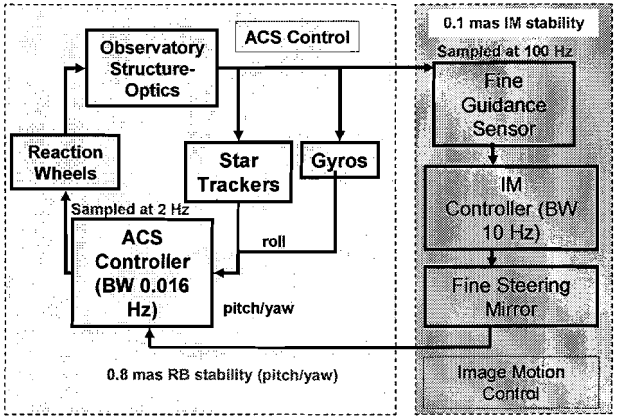
- AMS/secondary tower bracket & SMA isolators, launch struts (low conductivity)

M55J/954 GrEp

- AMS, secondary tower & bracket (good thermal stability & stiffness)

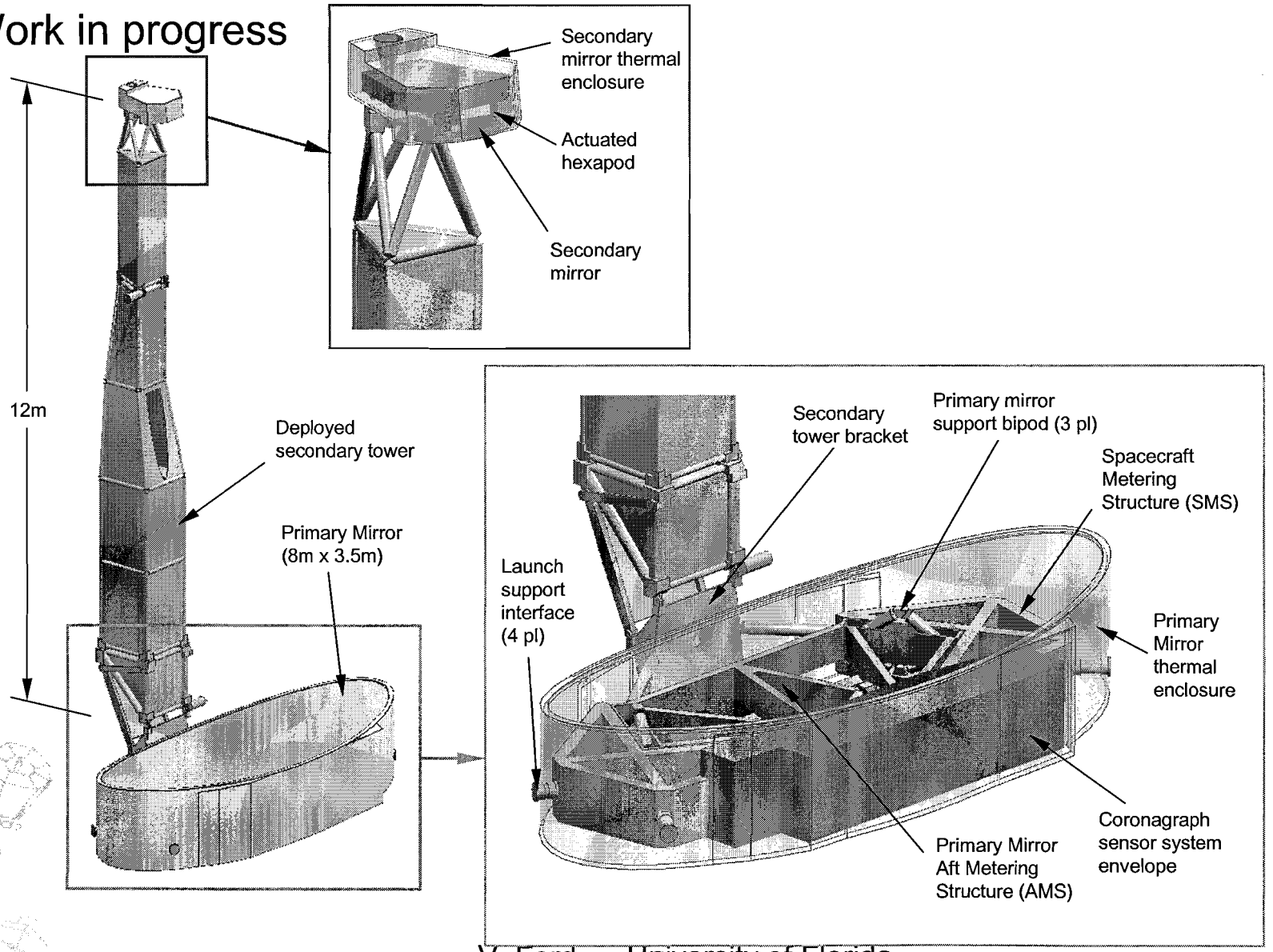






Flight Baseline Architecture – in work

- Many open trades
- Work in progress



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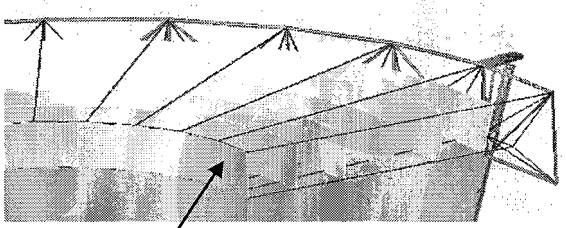
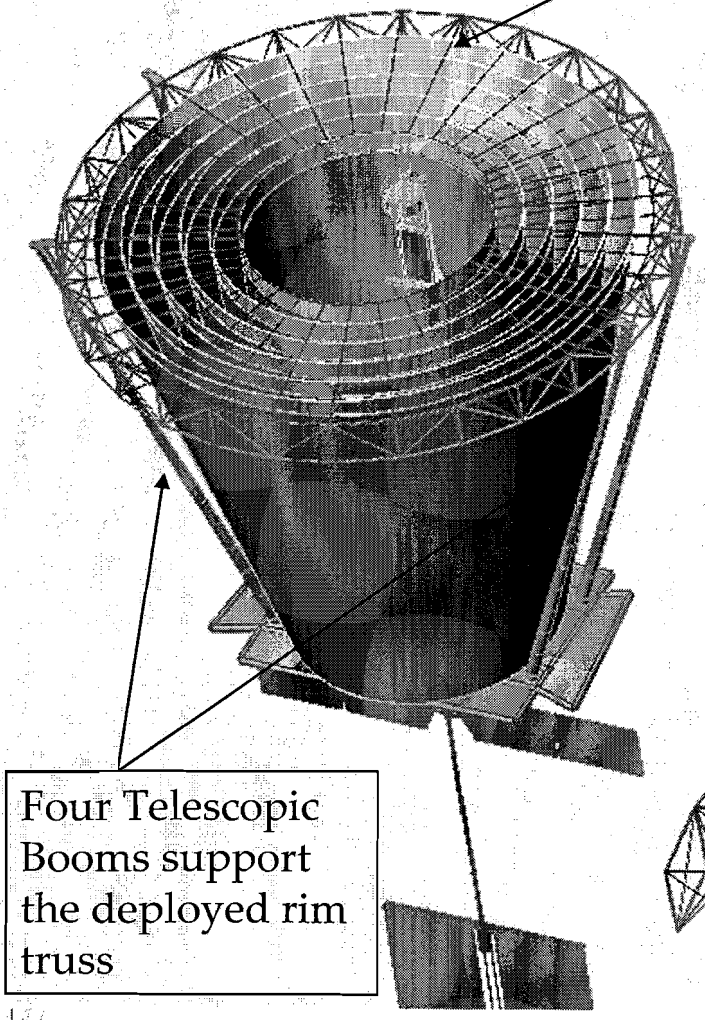
Astro Aerospace NGST Sun Shade work

A typical AstroMesh rim truss supports an array of radial cables.

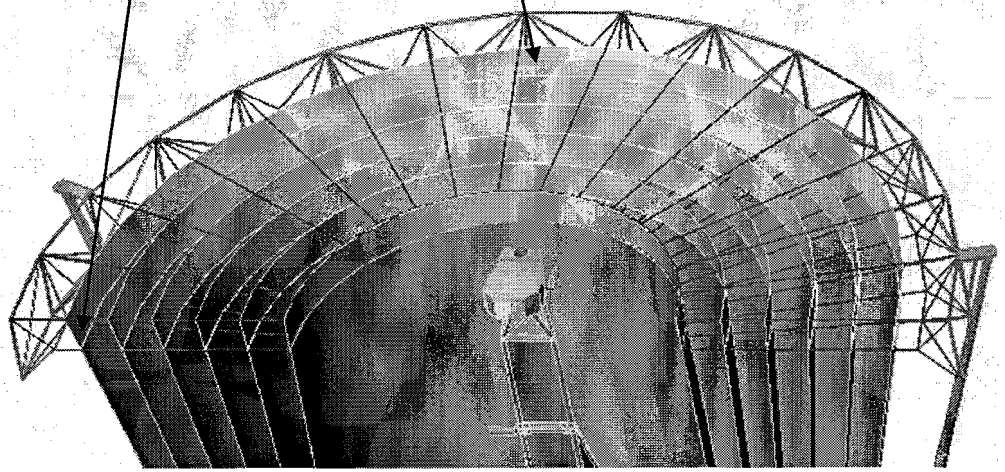
Shrouds are attached to lower radial cables



Shroud extensions between radials shield rim truss



Four Telescopic Booms support the deployed rim truss



Summary

- Starlight suppression research is advancing rapidly to approach the required contrast ratio
- The current analysis of the TPF Coronagraph system indicates that it is feasible to achieve the stability required by using developing technologies
  - Wave Front Sensing and Control (DMs, control algorithms, and sensing)
  - Laser metrology
- Yet needed:
  - Property data measured with great precision in the required environments
  - Modeling tools that are verified with testbeds

Stowed in Delta IV-H