LOCKHEED MARTIN
Ball Aerospace & Technologies Corp.
NORTHROP GRUMMAN Space Technology
TC Technology
nightsky systems

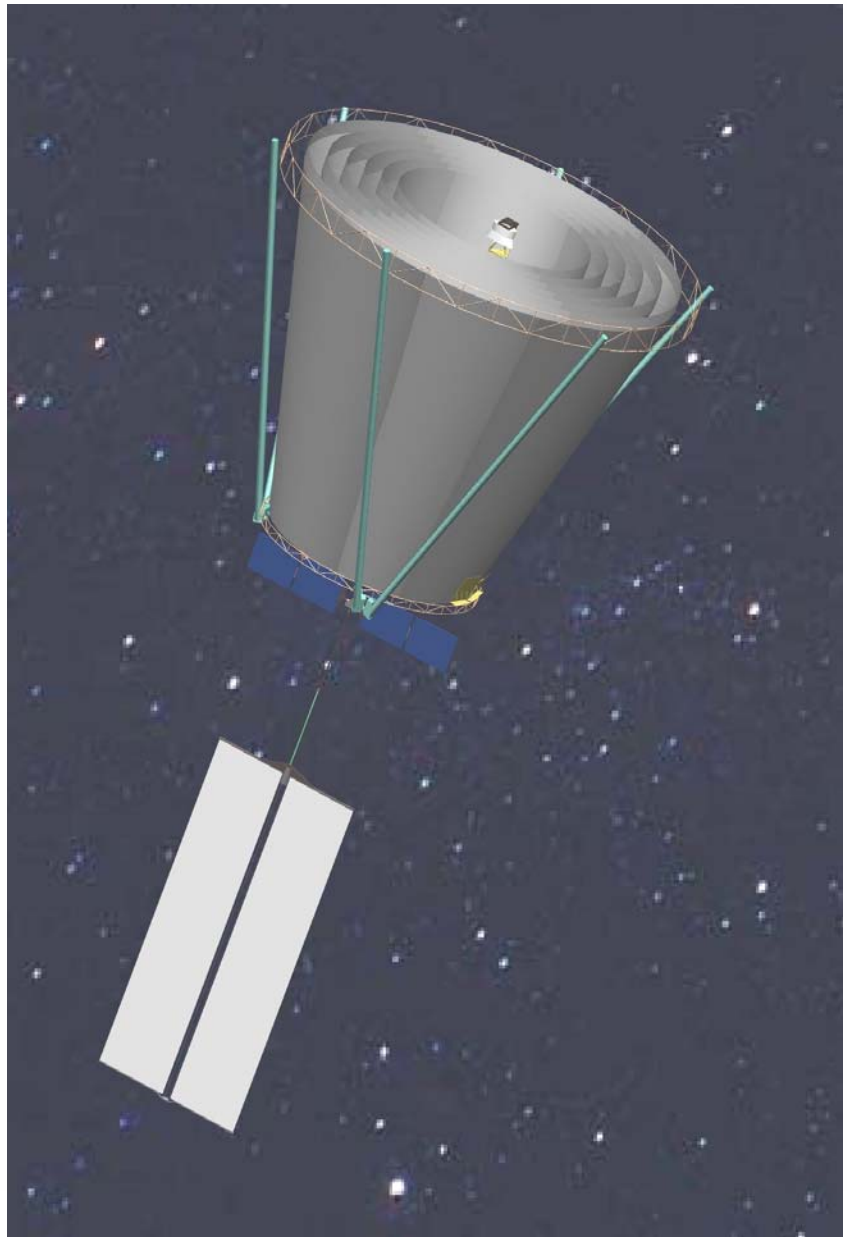
TPF Terrestrial Planet Finder

Introduction
TPF Coronagraph Flight Baseline 1 Design Presentation

Virginia Ford

Contributors: Tim Ho, Zeke Martinez, Richard Key, Jim Fanson

11-12 July 2005



Agenda

TPF Coronagraph FB1 Design Presentation
Room 410, Spitzer Science Center
California Institute of Technology, 1200 E. California Blvd, Pasadena
videocon: http://meetingplace.jpl.nasa.gov/a/86d05ace1a74dae63efc48e714275191
TPF Library location: https://tpf-lib.jpl.nasa.gov/tpf-lib/dscgi/ds.py/View/Collection-3137

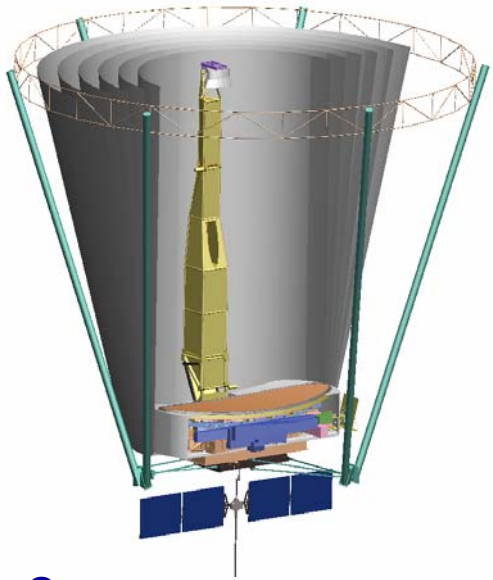
Start Time	Topic	Presenter
07/11/05		
7:30 AM	**COFFEE**	
8:00 AM	Welcome	Fanson
8:10 AM	Introduction	Ford
8:35 AM	Mission Description	Ford
9:00 AM	Summary of Science Performance	Hunyadi
9:15 AM	System Error Budget - description and plans	Shaklan
10:00 AM	**BREAK**	
10:15 AM	System Optical Design	Shaklan/ Ohl
11:15 AM	System Pointing Control Architecture & Design	Alexander
12:00 PM	**LUNCH**	
1:15 PM	System Mechanical Design & Configuration	Ho
2:15 PM	OTA Mechanical Desgin & Configuration	Engler
2:45 PM	System Thermal Architecture & Design	Cafferty
3:30 PM	**BREAK**	
3:45 PM	OTA Thermal Architecture & Design	Fantano
4:15 PM	I&T Plans	Martino
5:00 PM	General Discussion & Feedback	All
7:00 PM	**GROUP DINNER**	

07/12/05		
8:00 AM	**BREAKFAST DISCUSSIONS**	All
9:30 AM	Modeling Introduction & Plans	Levine
10:00 AM	System Optical Models, Performance Results & Future Studies	Palacios
10:45 AM	System Thermal Models, Performance Results & Future Studies	Eug
11:30 AM	**LUNCH**	
12:45 PM	System Structural Models, Performance Results & Future Studies	Kissil
1:30 PM	Primary Mirror Structural Models, Performance Results & Future OTA Studies	Irish
2:00 PM	**BREAK**	
2:15 PM	ACS Models, Performance Results & Future Studies	Blaurock
3:00 PM	Summary of Analysis results & impact on future design	Levine
3:15 PM	Proposed FB2 configuration changes: ACS trade studies	Alexander
3:30 PM	Proposed FB2 configuration changes: primary mirror shape and structure trade study	Green
3:50 PM	Proposed FB2 configuration changes: sunshade trade study	Cafferty
4:10 PM	Proposed FB2 configuration changes: mass reduction trade studies	Ho/Engler
4:30 PM	Proposed FB2 configuration changes: open back vs closed back primary mirror structure	Fantano
4:50 PM	General Discussion & Feedback	All
5:30 PM	**ADJOURN**	

"Pre-Registered" Attendees (approx.)

IN PERSON				VIA TELECON	
1	Andrew Smith	27	Larry Dewell	1	Alice Liu
2	Andy Kissil	28	Lou Fantano	2	Ann Merwarth
3	Andy Kuhnert	29	Luis Marchant	3	Daniel Polis
4	Bala Balasubramanian	30	Marie Levine	4	David Mozurkewich
5	Bill Reeve	31	Mark Marley (Tues)	5	Ed Groth
6	Bob Brown	32	Marty Levine (AM)	6	Edward Groth
7	Bob Woodruff	33	Michael Krim	7	Gary Matthews
8	Brent Abbott	34	Neil Martin	8	Gary Mosier
9	Carl Blaurock	35	Paul Atcheson	9	Hiedi Hammel
10	Charley Noecker	36	Peter Feher	10	Jeremy Kasdin
11	Chuck Bowers	37	Peter Halverson	11	Joe Howard
12	Chuck Engler	38	Ray Ohl	12	Lia LaPiana
13	Dave Content	39	Richard Key	13	Manuel Quijada
14	Dave Palacios	40	Rob Egerman	14	Marty Levine (PM)
15	Dick Dyer	41	Roger Angel (Tues)	15	Michael Werner
16	Dominick Tennerelli	42	Sally Heap	16	Rick Lyon
17	Don Lindler	43	Sandra Irish	17	Roger Angel
18	Eug Kwack	44	Sarah Hunyadi	18	Roger Brissenden
19	Fernando Tolivar	45	Scott Horner	19	Ruth Carter
20	Garth Illingworth	46	Steve Kilston	20	Sara Seager
21	Harry Ferguson	47	Stuart Shaklan	21	Steve Ridgeway
22	Jim Alexander	48	Terry Cafferty	22	Steve Unwin
23	Jim Fanson	49	Tim Ho	23	Tom Williams
24	Jim Kasting	50	Tony Martino	24	Vern Weyers
25	Joe Green	51	Virginia Ford		
26	John Lou				

TPF Coronagraph System Objectives



What? TPF Coronagraph Observatory

- Large very fine primary mirror
- Wave front sensing and control with Deformable Mirror and camera
- Starlight suppression – baseline via focal and pupil plane masks and stops
- Control of diffraction and polarization effects
- Very stable structural and thermal control
- Very accurate modeling of wavefront propagation, component effects, structural and thermal performance
- Integral Field Spectrometer
- Additional Astrophysics instruments

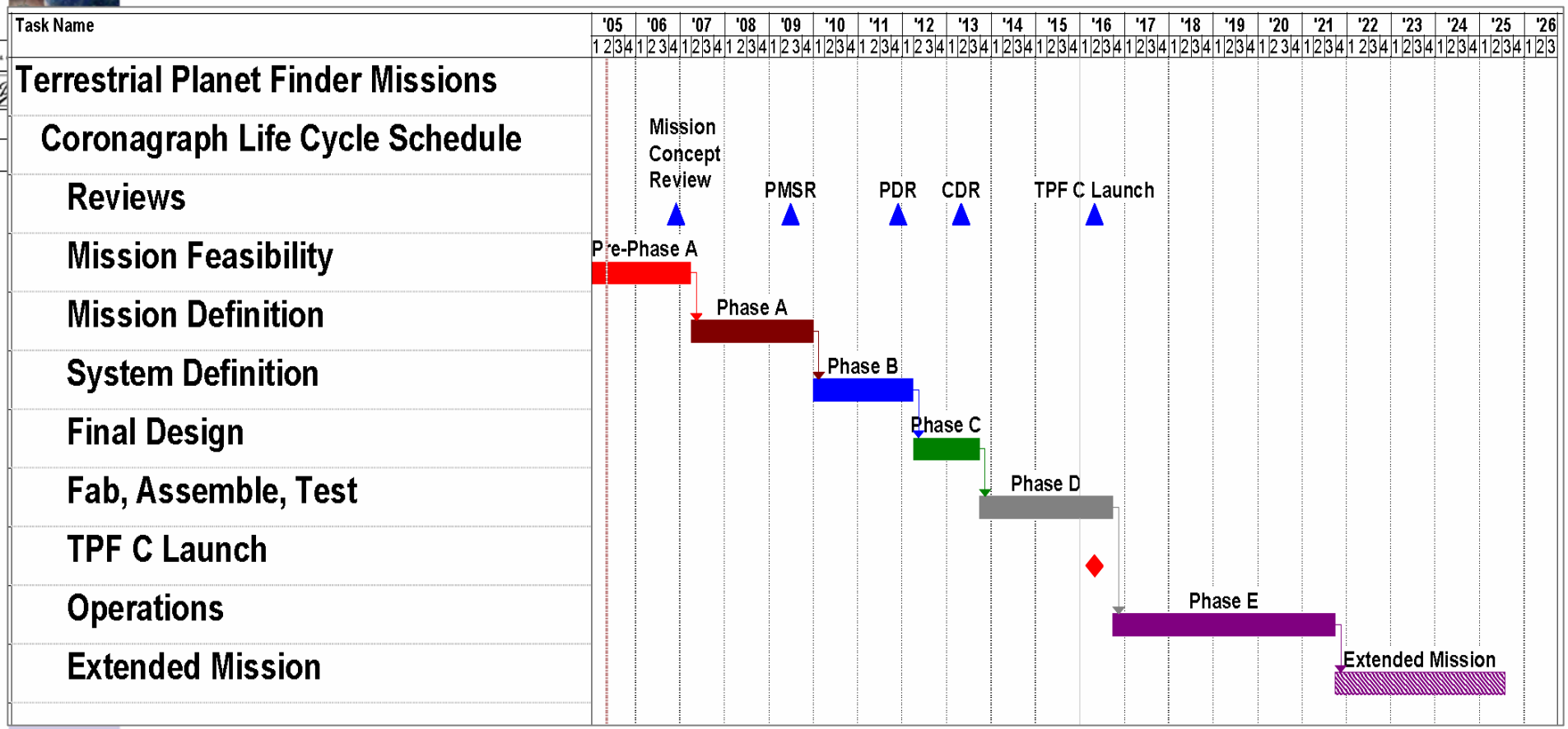
Why?

- By performing wavefront correction, the scatter and diffraction from the classic telescope can be adequately controlled so that faint light from a planet next to a star can be detected
- The light from a detected planet and re-visits can validate that a planet is found and be evaluated for spectral bio-signatures
- Fine quality telescope and imaging will be used for other astronomy

How?

- Develop and improve state-of-the art technology (test bed, DM, Mask & Stops, modeling tools)
- Model performance of components and verify through test bed experiments
- Fabricate large demonstration mirror to develop road map to meet TPF primary mirror reqts
- Analyze, develop and evaluate coronagraphic architectures and perform trades that lead to selection of optimum flight mission design

TPF Coronagraph Current Life Cycle Schedule



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

Entire TPF-C Effort

Pre-Phase A Schedule based on 2005 POP Budget

JPL

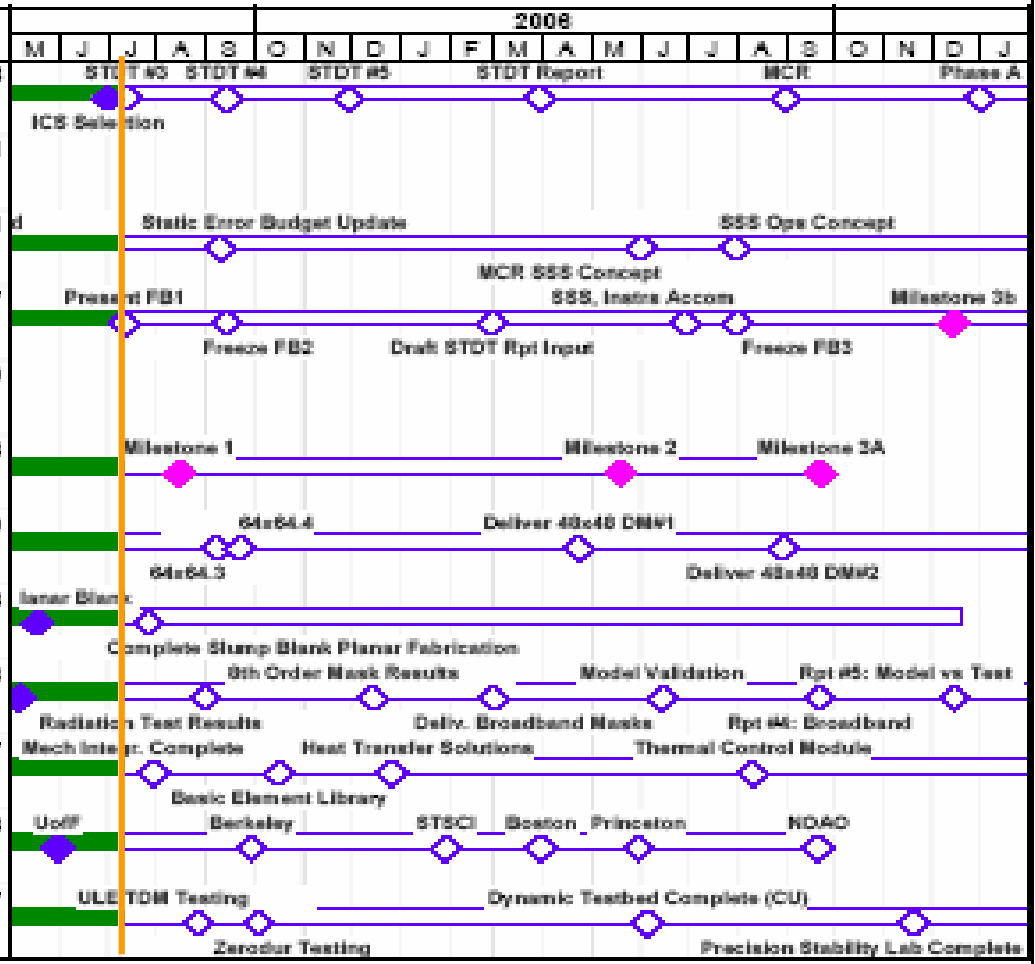
Responsibility: Jim Fanson
Revision Date: 7/8/05 3:06 PM

TPF-C Level 1

TPF-C

Project Schedule Analyst: Ezequiel Martinez
http://sched-central.jpl.nasa.gov/

ID	Name	Start	Finish
1	Project Phase/Reviews	1/8/03	2/1/18
13	Conceptual Design	4/1/02	8/9/11
14	Coronagraph Architecture	11/3/03	8/9/11
23	Coronagraph Design Team	4/1/02	3/23/07
48	Technology / Testbeds	1/2/03	4/14/09
47	High Contrast Imaging Testbed	10/4/04	8/22/08
62	Xinetics	8/2/03	4/14/09
68	Technology Demonstration Mirror	8/18/03	12/19/08
82	Masks & Stops Development	1/2/03	8/11/08
72	Integrated Modeling Tools	8/20/03	4/19/07
86	University Contracts Schedule	11/3/03	8/21/08
93	Mechanical Stability Characterization	8/24/04	7/18/07



Milestone 1: Narrow Band Contrast
Milestone 2: Broadband Contrast
Milestone 3a: Modeling Validation
Milestone 3b: Use Model to Achieve 10^-10 Contrast

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TPF-C Design Cycle Schedule

		CY 2004				CY2005				CY2006				
		FY 2004				FY2005				FY2006			FY2007	
	end date	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2
Project Phases															
Pre Phase A	1/3/2007														
Phase A	1/3/2010														
Project Reviews and Meetings															
SWG/TIM															
STDT															
Mission Concept Review	9/15/2006														
Major Project Milestones															
Design Concept Cycles															
Minimum Mission Design Concept															
Design Concept Development	1/15/2004														
Freeze MM Baseline	1/20/2004														
MM Modeling and Analysis	4/9/2004														
Minimum Mission Report	4/22/2004														
Flight Baseline 1 Design Concept															
Design Concept Development	1/20/2005														
Freeze FB1 Baseline	1/20/2005														
FB1 Modeling and Analysis	10/7/2005														
Design Presentation	7/11/2005														
Flight Baseline 2 Design Concept															
Design Concept Development	10/7/2005														
Freeze FB2 Baseline	10/7/2005														
FB2 Modeling and Analysis	2/15/2006														
Mission Description Draft Inputs	2/15/2006														
Flight Baseline 3 Design Concept															
Design Concept Development	7/28/2006														
Freeze FB3 Baseline	7/28/2006														
FB3 Modeling and Analysis	12/10/2006														

STDT#1 STDT#3 STDT#5 Report
STDT#2 STDT#4
MCR
Milestone 1[1] Milestone 2[2] Milestone 3b[4]
Milestone 3a[3]

Goal for TPF-C Design Concept Cycles

Minimum Mission Concept

- Develop modeling and analysis process to enable contrast performance assessment with on-orbit thermal and dynamic perturbations
- Evaluate stability requirements and feasibility to meet them
- Cursory launch loads analysis

Cycle 1 – Flight Baseline 1 Design Concept (FB1)

- More Detailed Design
  - Include placeholder instruments, payload passive thermal control, Secondary Mirror assembly details, sun shade details, instruments, passive thermal control of payload
  - Larger, more difficult primary mirror with more detailed mounting
- Modeling advancement
  - Advance contrast performance modeling
  - Improve understanding of thermal and dynamic perturbations and model issues
- Launch loads analysis
- Determine thermal sensitivity leading towards active thermal control system design

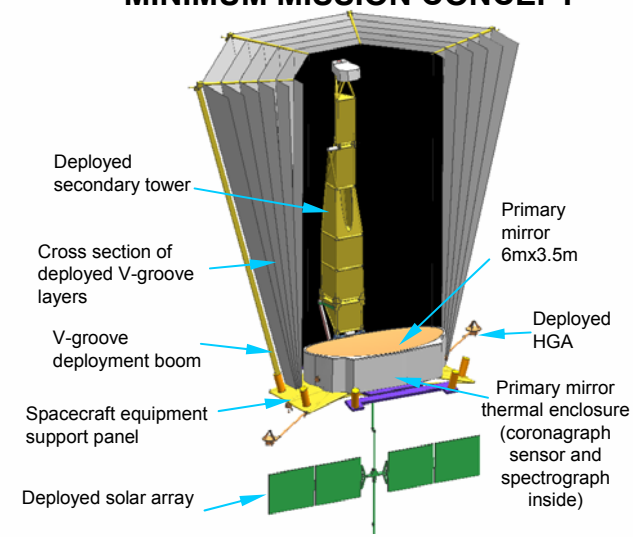
Cycle 2 – Flight Baseline 2 Design Concept (FB2)

- Implement active thermal control
- Understand instrument accommodation issues
- Refine observatory design based on FB1 results and comments
- Reassess and advance modeling and contrast performance
- Prepare for AO for instrument selection

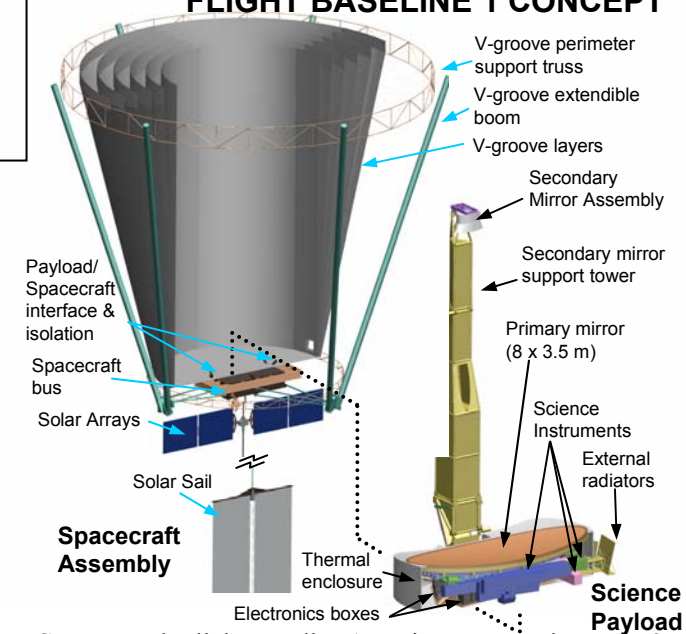
Cycle 3 - Flight Baseline 3 Design Concept (FB3)

- Meet contrast performance goal for Milestone 3b
- Evaluate and change concept and models as needed
- Update instrument accommodations and details

MINIMUM MISSION CONCEPT



FLIGHT BASELINE 1 CONCEPT



Meeting Intended Results

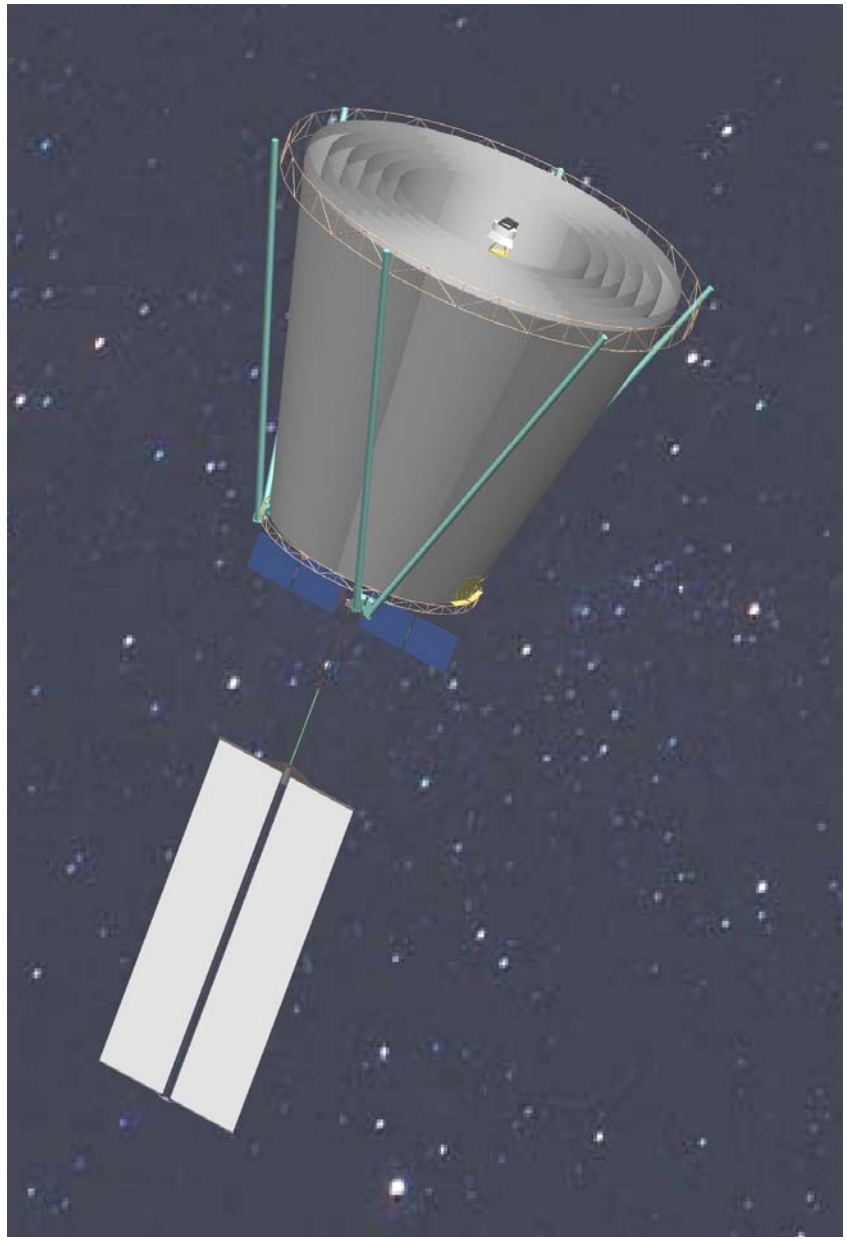
- Inform TPF-C community of our status
  - Full two days worth of presentation
  - Some discussion time planned for each section
  - Comment forms are supplied to capture comments and topics for extended discussion
- Do not expect a flight-ready design concept
  - In pre-phase A need to work on advanced concepts and establish feasibility
  - We have limited resources:
    - Haven't spent much on standard engineering areas (our judgment)
      - Orbit, Launch, Spacecraft detail
      - I&T except in the telescope area
    - Some areas just aren't well covered
      - Software Definition
      - Ground support definition
- Do not expect to see a completed analysis
  - We are in final stages of FB1 analysis portion
  - Work is not complete but detailed schedule and plans are in place
  - Status is being presented
- Receive comments that will guide design choices for Flight Baseline 2
  - Please use comment forms to:
    - Capture your input correctly
    - Reduce extended discussion – keep to our schedule
  - FB2 choices are not finalized – we intend to use the comments we receive in our trade studies

Mission Description

Virginia Ford

Contributors: Doug Lisman, Peter Feher, Sarah Hunyadi, Architecture and Design Team

11-12 July 2005



Mission and Spacecraft Choices for FB1

Lisman and Feher

	Parameter	Value	Comments
Mission	Duration required/goal	5/10 years	Resources for 10 years
	Orbit	L2	Direct trajectory
	Field of Regard	Sun angles > 95°	Potential earth/moon/planet constraints
	Required ΔV	60 m/s	
	Launch Energy (C_3)	-0.69 km^2/s^2	
	Launch Vehicle	EELV	
	Launch Fairing	5 m diameter	limits primary mirror short axis to ~3.5 m
	Launch Mass	9200 kg	
	Time to reach operating orbit	109 days	
	Ground Station	34m DSN Ka-Band	
	Downlink Data Rate	64Mbps	
Spacecraft	EOL Power	3kW	provided by solar arrays
	Reaction Wheels	6 Ithaco- E	
	Propellant	242 kg Hydrazine	
	Thrusters	12 20N	
	Hi Rate Downlink Frequency	Ka-Band	avg duration 2.5 hours per day
	Engineering Downlink Frequency	X-Band	
	Uplink Frequency	X-Band	
	Transmitter Power	50W	
	Hi Gain Antenna	43dB	0.5m patch array

FB1 Estimated Mass

Lisman and Feher

Component	Mass Estimate (kg)	% of Total Launch Mass
Payload	5540	
Telescope	3440	43.5
Payload Support Subsystem	1508	19.1
Starlight Suppression Subsystem	412	5.2
Planet Detection Camera	10	0.13
Planet Characterization Spectrometer	20	0.3
General Astrophysics Instrument	150	1.9
Spacecraft	2374	30.0
Total Launch Mass	7914	
Launch Vehicle Capability	9200	
Launch Margin	**1336**	
Launch Margin (%)*	**14.4**	

Note: there is an upcoming presentation on mass reduction trade studies for FB2

*Defined as (LV Capability-Total Estimate)/Launch Capability

FB1 Estimated Power Usage

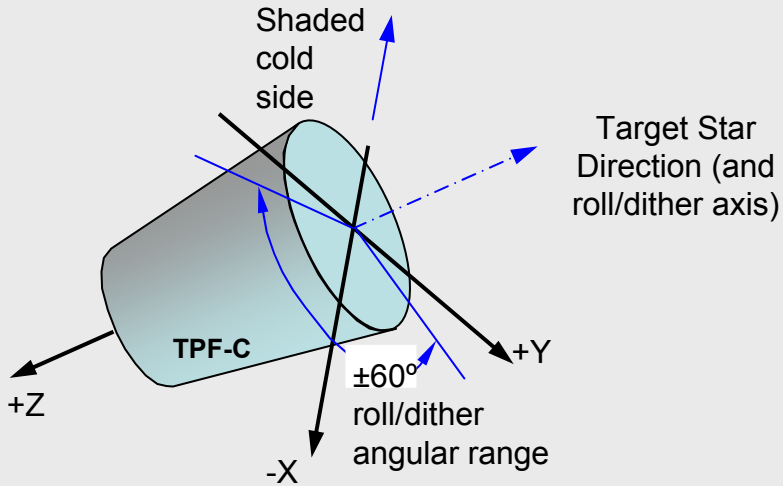
Lisman and Feher

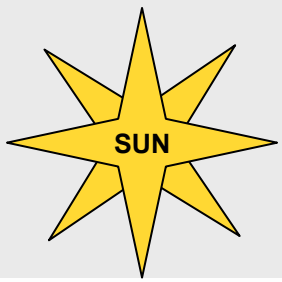
	Power Estimate (W)	% of Total Power
Payload	1049	51.2
Telescope including thermal control	664	32.4
Payload System Electronics and thermal control	156	7.6
Starlight Suppression Subsystem	87	4.2
Planet Detection Camera	2	0.1
Planet Characterization Spectrometer	40	2.0
General Astrophysics Instrument	100	4.9
Spacecraft	1000	48.8
Total Power	2049	
Available EOL Power	3000	
Power Margin (W)	**951**	
Power Margin (%)*	**32**	

*Defined as (Available Power-Total Estimate)/Available Power

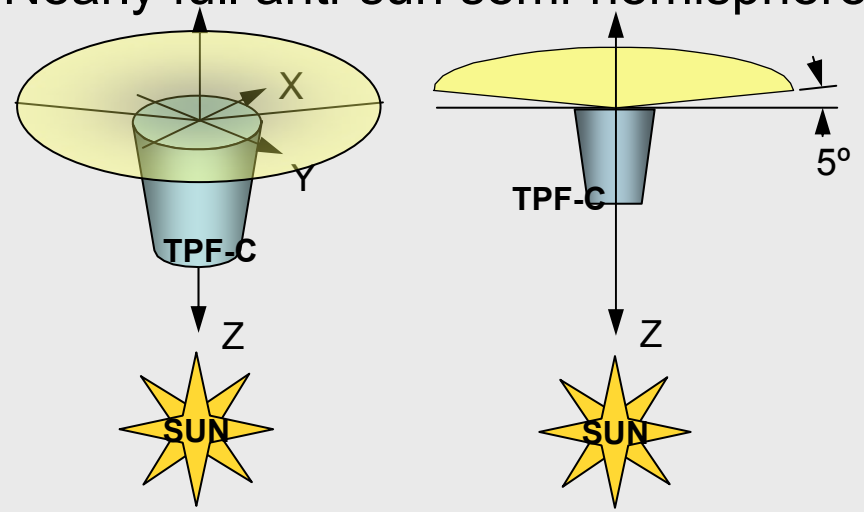
FB1 Observing Scenario

Observation of each target star





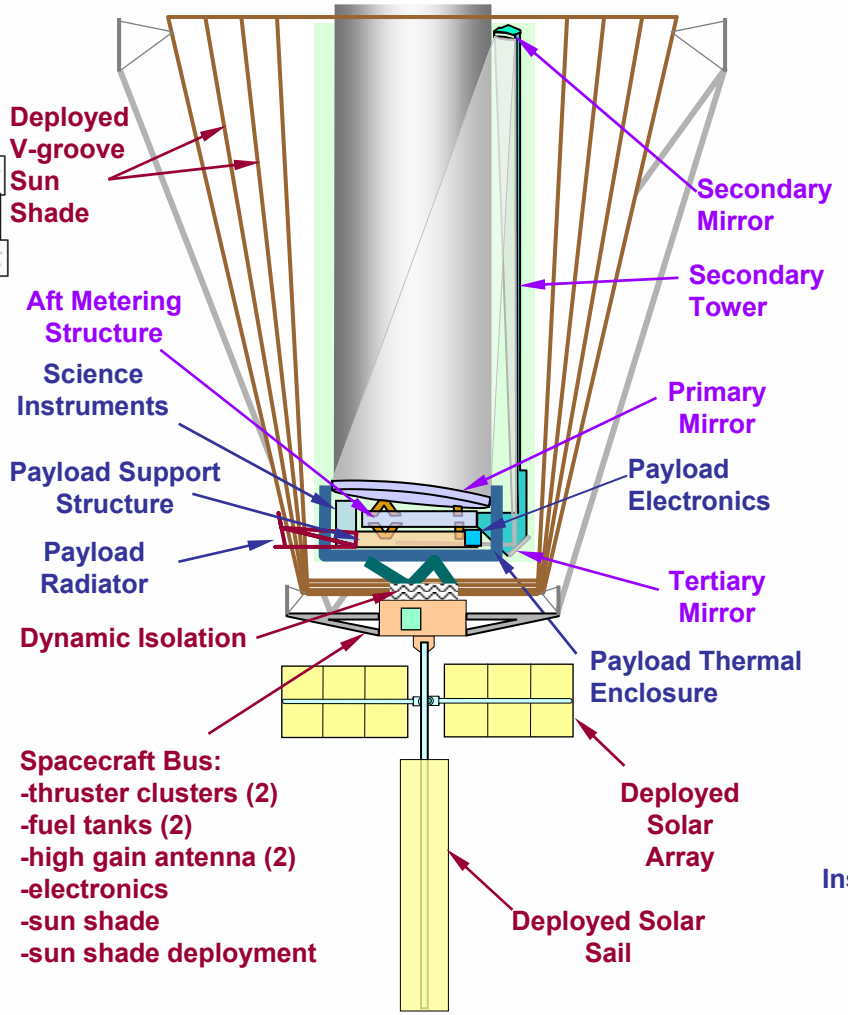
Observatory Field of Regard – Nearly full anti-sun semi-hemisphere



Discovery Scenario:

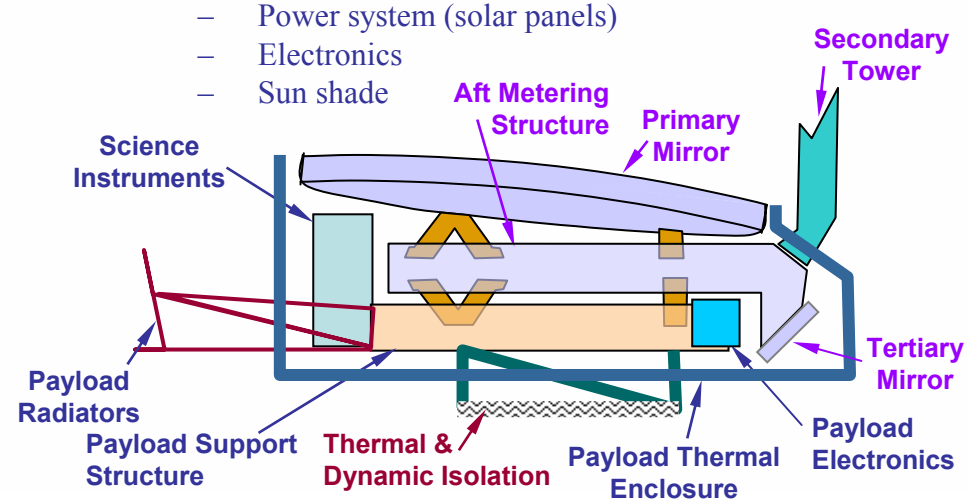
1. Acquire target star
2. Stabilize dynamics and collect light
3. Using Adaptive Optics, suppress star light
4. Dither 30 degrees
5. Stabilize dynamics and collect light
6. Subtract images
7. Roll to next 60 degree orientation
8. Repeat 2 through 6 two times

Payload Mechanical Interfaces



KEY
Spacecraft
Telescope
Other Payload

- Telescope
  - Primary, Secondary and Tertiary Mirror Assembies
  - Secondary Mirror Tower
  - Aft Metering Structure
  - Thermal control hardware
  - Laser Metrology
- Payload Excluding Telescope
  - Structure mounting payload to Spacecraft through thermal and dynamic isolation components
  - Starlight Suppression System
  - Science Instruments
  - Thermal control components- heat pipes, radiators, Isothermal enclosure
  - Payload Electronics
- Spacecraft
  - Navigation components
    - Thrusters, Reaction Wheels, Solar sail, Fuel tanks
  - Communication components
  - Power system (solar panels)
  - Electronics
  - Sun shade



Trade studies – pg 1

	Agreed on study - incorporate in FB2	Requires analysis results - Decide prior to FB2 Freeze	Defer to FB3	After FB#3 (Phase A)
1.0	**Mission - orbit detail, ΔV, Launch Vehicles, mission duration**			
	may pad ΔV to be conservative			
2.0	**Starlight Suppression System alternatives**			
2.1	**Consider alternates to dither maneuver for speckle removal (per NRA concepts)**			
2.2	**Consider series DMs, remove beam-splitters, redundancy**			
2.3				
2.4	**Consider increasing OWA for giant planets with larger DM, FOV for dust disk observations**			
2.5	**Consider longer wavelength observations (per NRA concepts) up to about 0.9µm**			
2.6	**Evaluate anamorphic optics compared to larger DM**			
3	**Instruments accommodations**			
4	**Pointing and Control - active vs passive dynamic isolation**			
4.1	**Define frequency range and control loop bandwidths, assess compatibility with actuator capabilities**			
4.2	**Evaluate necessity of secondary mirror steering, pending capability of payload vibration isolator**			
4.3	**Evaluate mounting of payload Payload Acquisition Camera, evaluate changes to reaction wheels**			

Trade studies – pg 2

	Agreed on study - incorporate in FB2	Requires analysis results - Decide prior to FB2 Freeze	Defer to FB3	After FB#3 (Phase A)
5	Primary Mirror			
5.1	Consider shape changes - increased depth and 8x3m race-track vs elliptical PM shape			
5.2	Open vs. Closed back PM structure evaluation			
5.3	Evaluate PM actuators vs. Coarse DM			
5.4	Resolve PM launch load issues - configuration change to reduce loads or add dampers/absorbers			
6	Mass Management			
6.1	Redesign thermal enclosure/Secondary Tower/AMS/LD5 boxes - mass efficient stiffness, add 4 arcmin FOV			
6.2	Add mass estimates for: launch constraints, dust covers, ballast, identify load bearing mass			
6.3	Evaluate mass sensitivity to: PM frequency, vibration control, SM actuation, metrology, solar sail			
7	Solar Array - Consider alternatives			
8	Solar Sail - improve design for better torque balance			
9	Sunshade - consider alternatives, add degradation features, trade performance against stowing/deploying issues			

Trade studies – pg 3

	Agreed on study - incorporate in FB2	Requires analysis results - Decide prior to FB2 Freeze	Defer to FB3	After FB#3 (Phase A)
10	Stray Light - develop concept for telescope baffles, add vanes, deployment issues			
11	Define viewing constraints from earth, moon, Jupiter, etc.- characterize vs. orbit size/position			
11.1	Contamination: understand requirements, add covers on exposed optics as required			
12	Thermal Control - incorporate active thermal control			
12.1	Consider thermal configuration changes - electronics mounting, heat pipe dynamics, alternate approaches			
13	I&T design issues			
13.1	Select OTA test configuration, incorporate features in flight design			
13.2	Understand required flight jitter requirement - use to evaluate chamber availability and testing capability			
13.3	Understand required flight thermal gradient requirements - use to evaluate chamber availability and testing capability			
13.4	Trade optical concepts for OTA tests - sub-aperture test requirements, model system, define requirements			
14	Software Definition			
15	Ground Segment Definition			

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nightsky systems

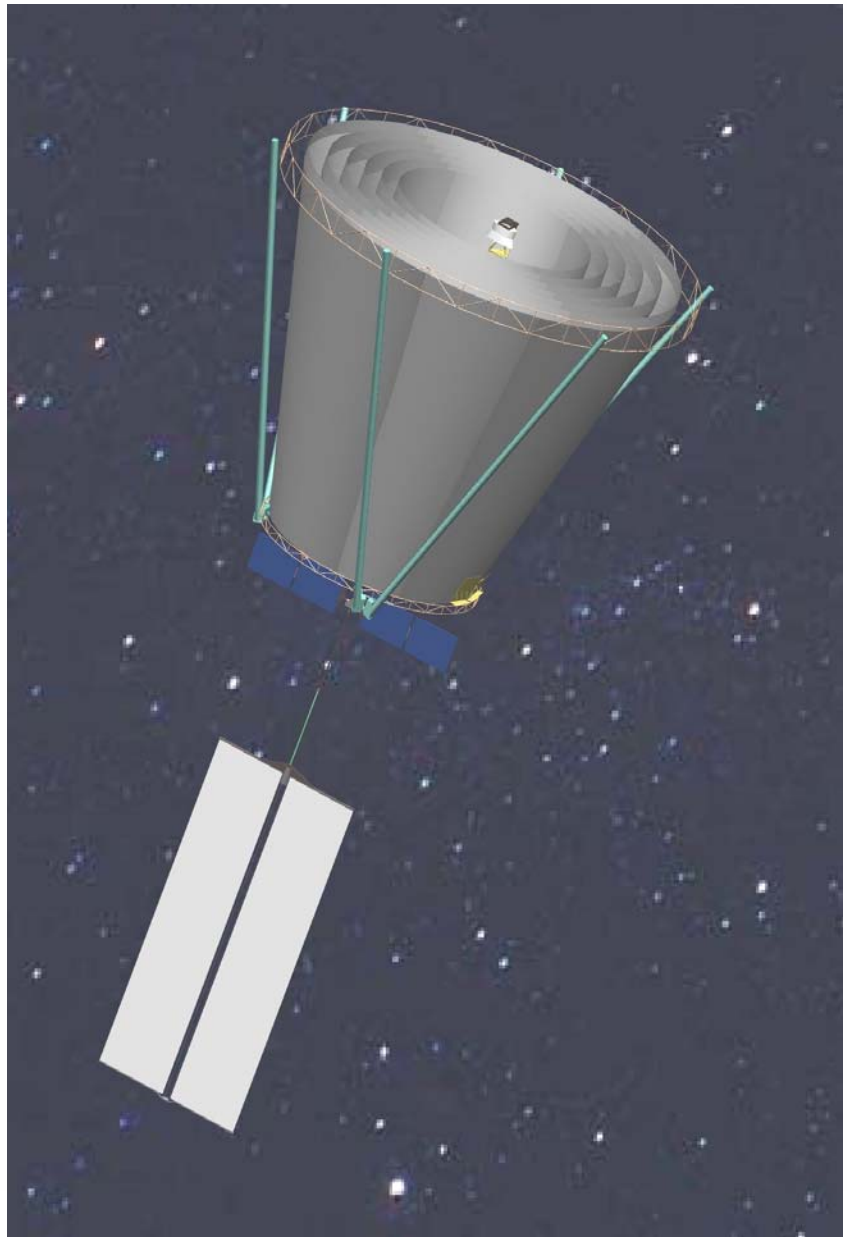
TPF Terrestrial Planet Finder

Completeness Update

Sarah Hunyadi

Contributors:
Stuart Shaklan
Bob Brown

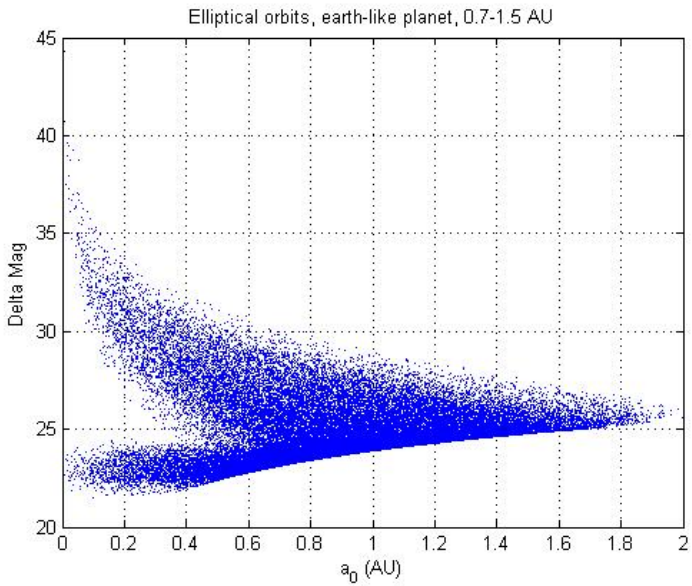
11-12 July 2005

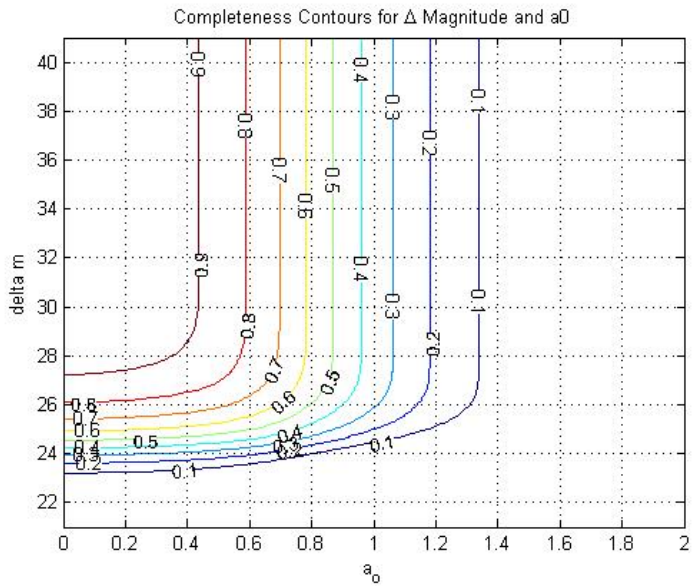


Overview

- Update of ongoing completeness analysis with Stuart Shaklan and Bob Brown
- Change from circular to elliptical orbits
- Synchronization of integration times
- Optimization of single visit completeness
  - Bob Brown employs an auction optimization
  - JPL employs an efficiency cutoff optimization
  - These two are shown to be equivalent
- Now using best estimate system throughput
- First iteration of program completeness optimization

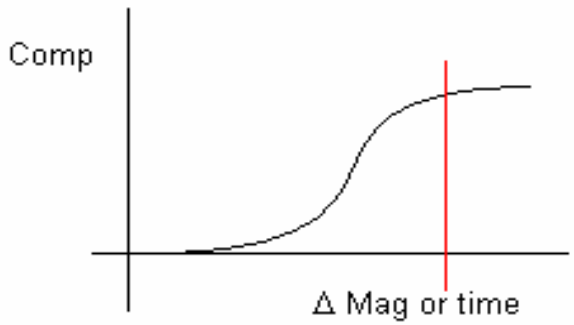
Completeness

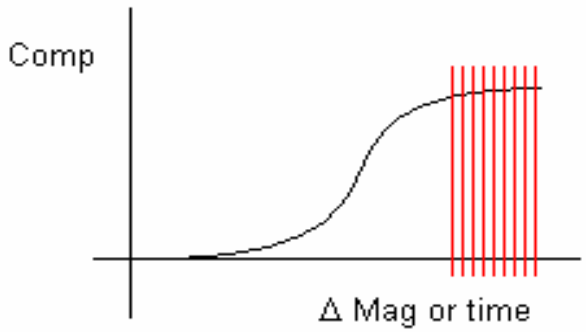




- Elliptical orbits extend range of habitable zone orbits
- Integrate elliptical planet distribution over a_0 and IWA to obtain completeness contours
- Contours are shifted for stellar luminosity and distance to obtain completeness vs. delta magnitude
- Noise and flux calculations give integration time vs. delta magnitude

Single Visit Auction Comparison –
for detection of earth-equivalent planets





- JPL optimization uses an iterated efficiency cutoff factor to eliminate all time from star that falls below the efficiency cutoff.
- Brown optimization cuts time from a star, hour by hour, based on lowest incremental efficiency.

Both programs then optimize over number of hours cut, keeping one year of integration time to obtain the maximum cumulative completeness.

	JPL		Brown	
ΔMag	# Stars	# Planets	#Stars	#Planets
25	138	32.60	135.21	32.59
25.5	125	38.29	122.77	38.32
26	115	41.10	113	40.96
27	114	42.16	106	41.04

New Throughput Parameters

Old Assumptions

- SNR=10
- IWA= 0.057 arcsec
- 0° dither
- Lyot throughput = 50%
- System throughput = 21%
- Total throughput w/ CCD QE = 17.0%
- Circular orbits

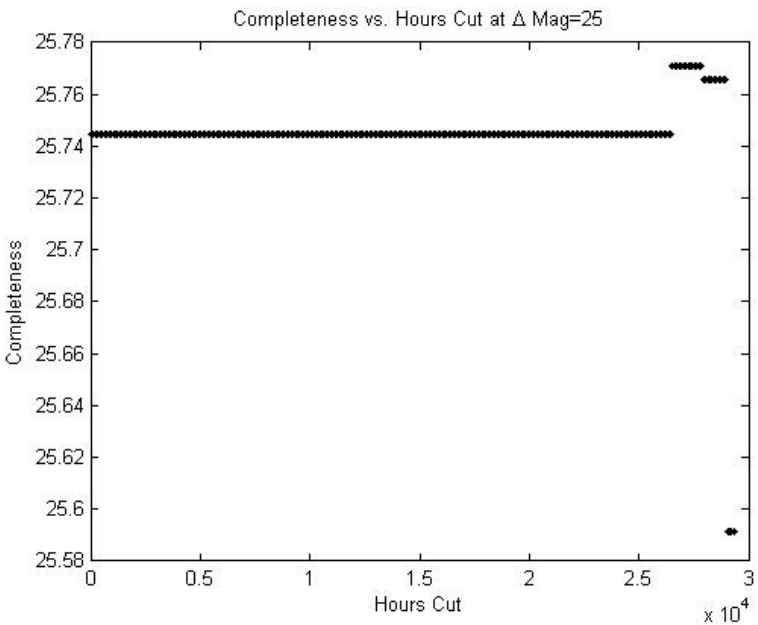
New Assumptions

- SNR=5
- IWA= 0.0655 arcsec
- 30° dither
- Lyot throughput = 34%
- System throughput = 10.8%
- Total throughput w/ CCD QE = 8.64%
- Elliptical orbits

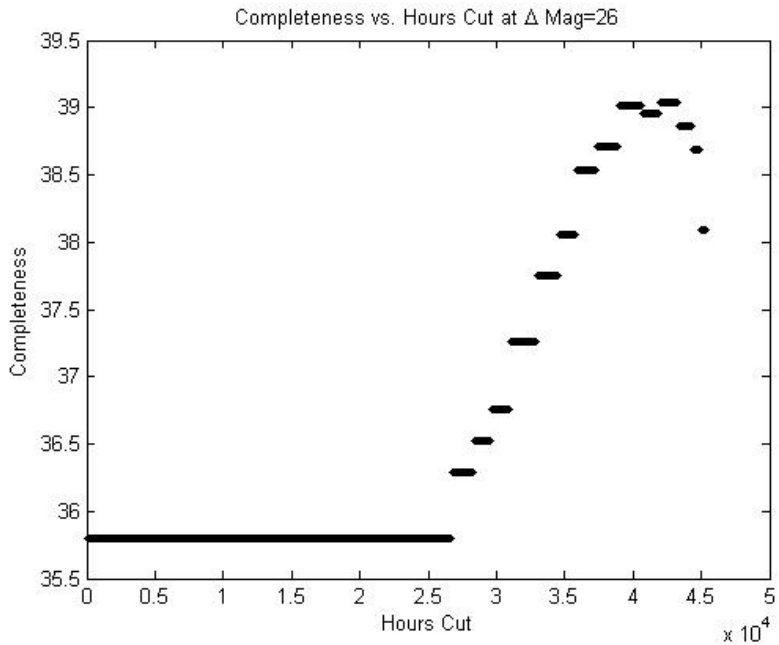
Common Parameters

- Telescope = 8x3.5 m ellipse
- CCD QE = 0.8
- Integration time = 1 year
- Central wavelength = 550 nm
- Bandpass = 110 nm
- 3 rolls

Preliminary Parameter Auction Results



ΔMag = 25

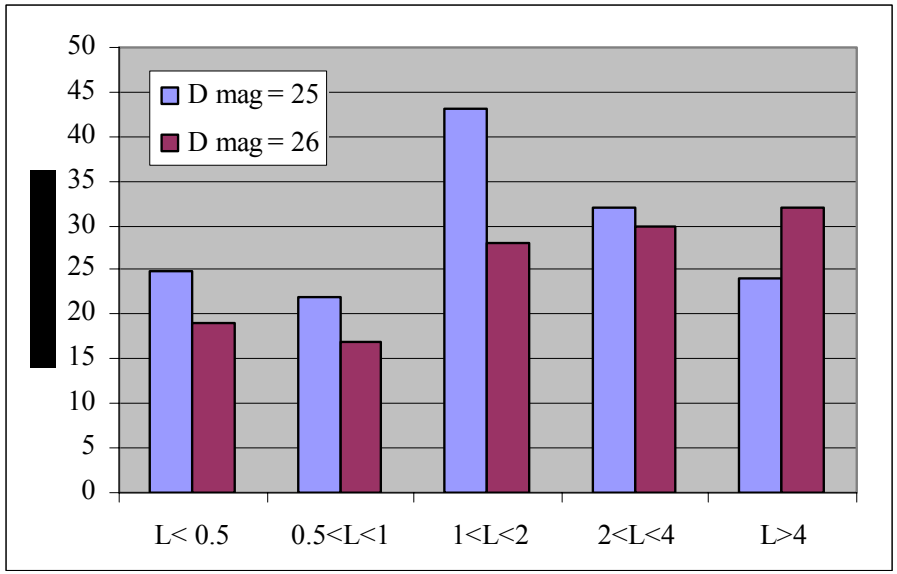


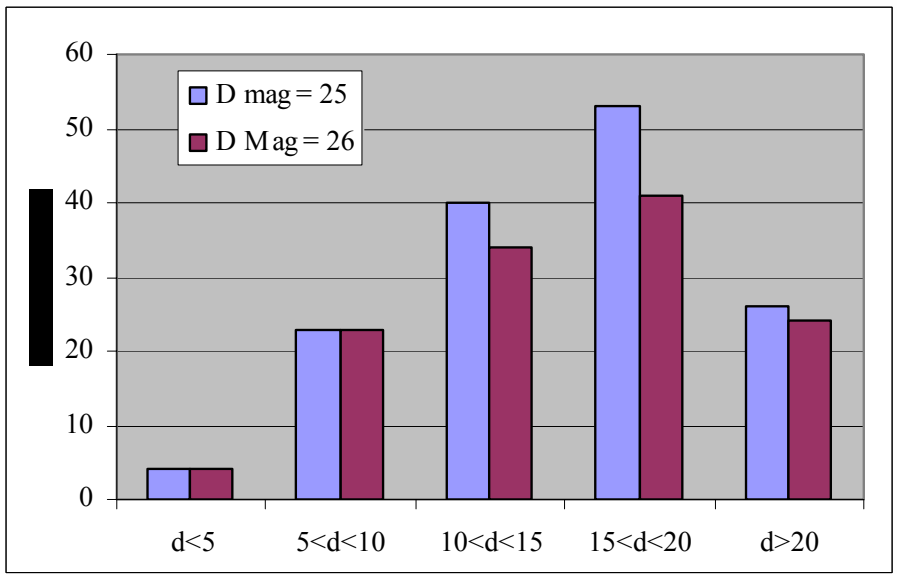
ΔMag = 26

- Planets = 25.771 (JPL)
- Planets = 26.13 (Brown)
- Participating Stars = 146
- Little improvement over ΔMag=25 (flat line)

- Planets = 39.038
- Participating Stars = 126
- Significant improvement over ΔMag=25

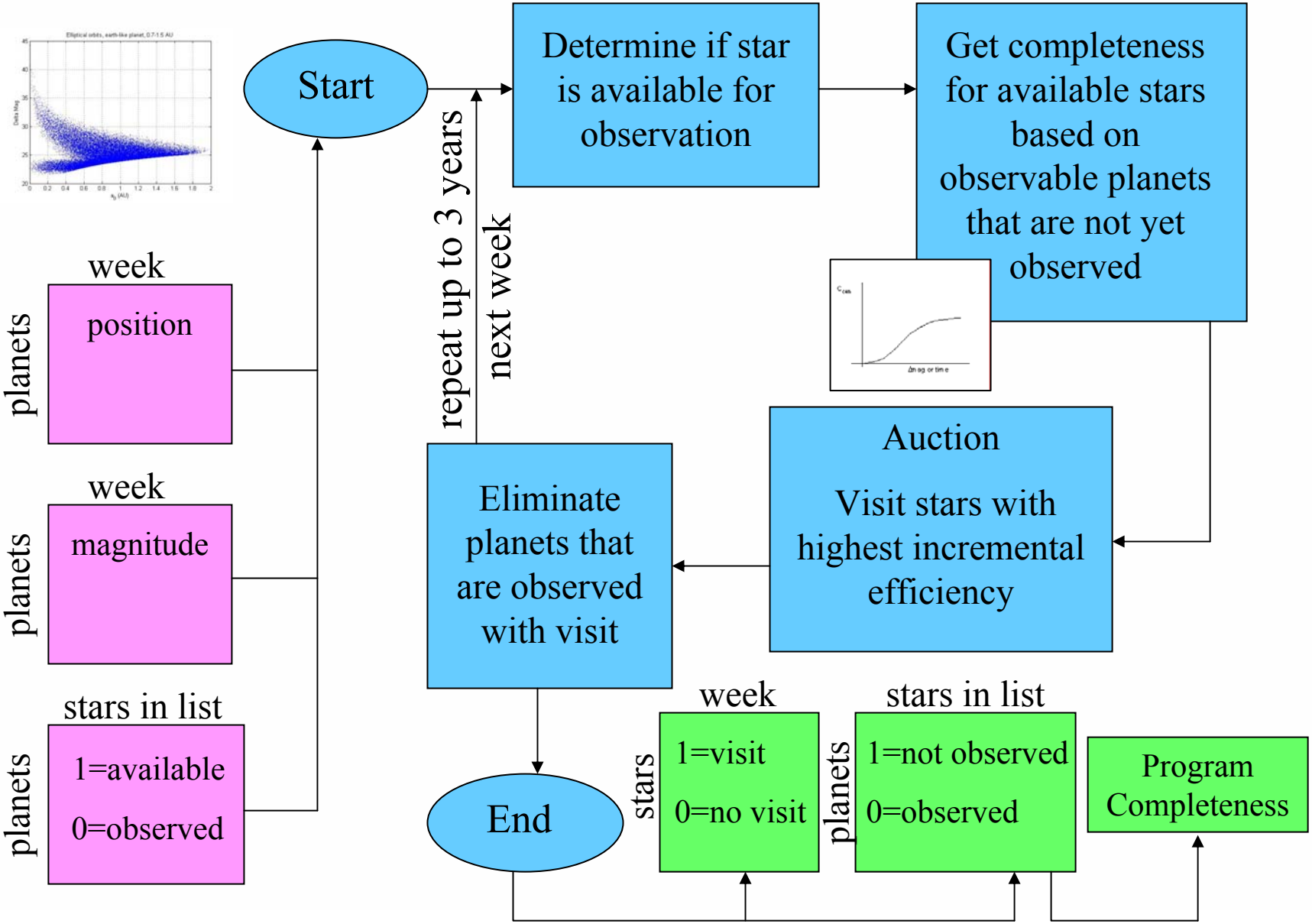
ΔMag=25 and ΔMag=26 Comparison





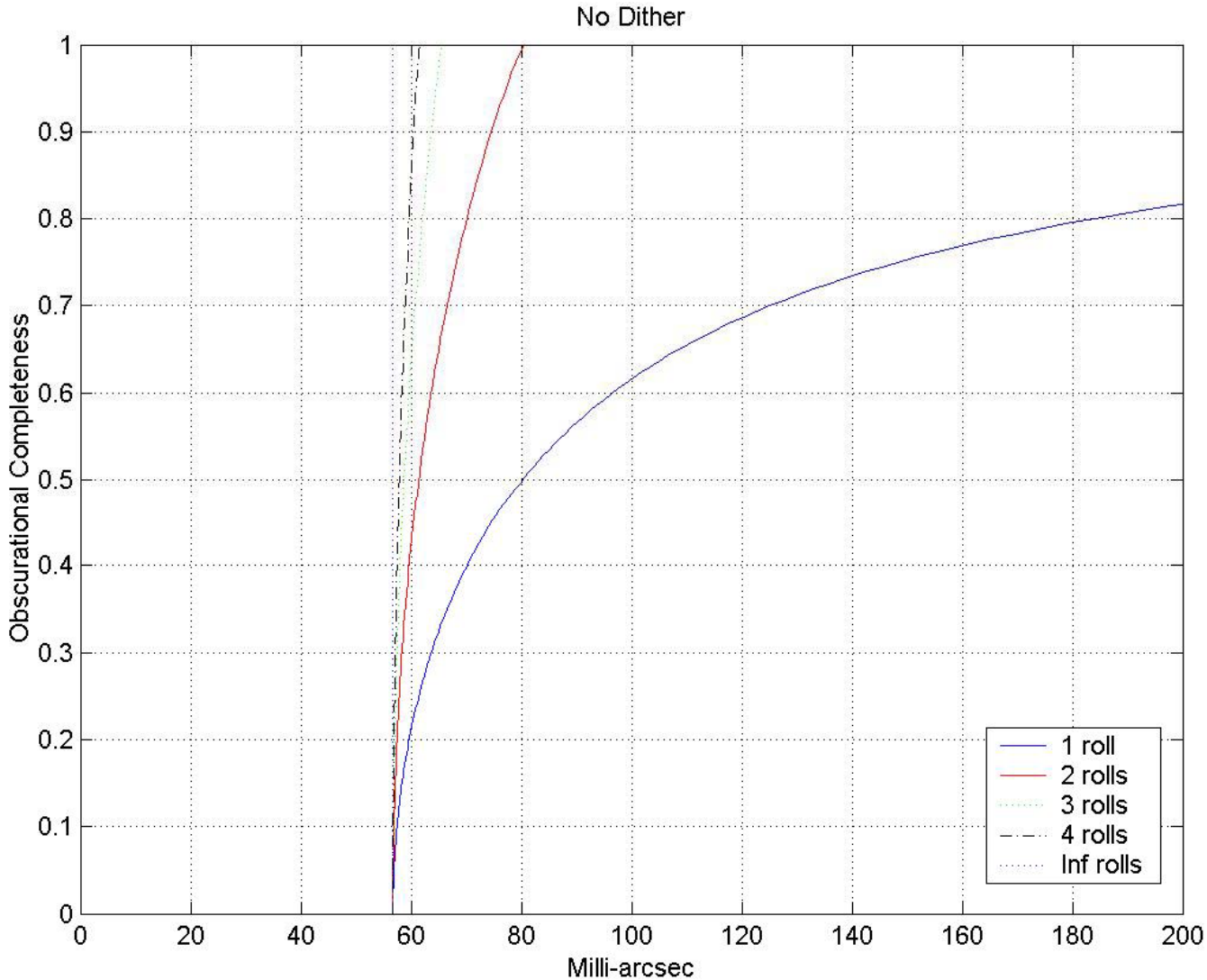
- ΔMag=25
  - 146 stars
  - 25.77 planets
- ΔMag=26
  - 126 star
  - 39.04 planets
- For ΔMag=26 more high luminosity stars are visited
- Fewer number of stars, but much higher planet count
- Can view stars deeper and observe planets that are 2x fainter

Program Completeness

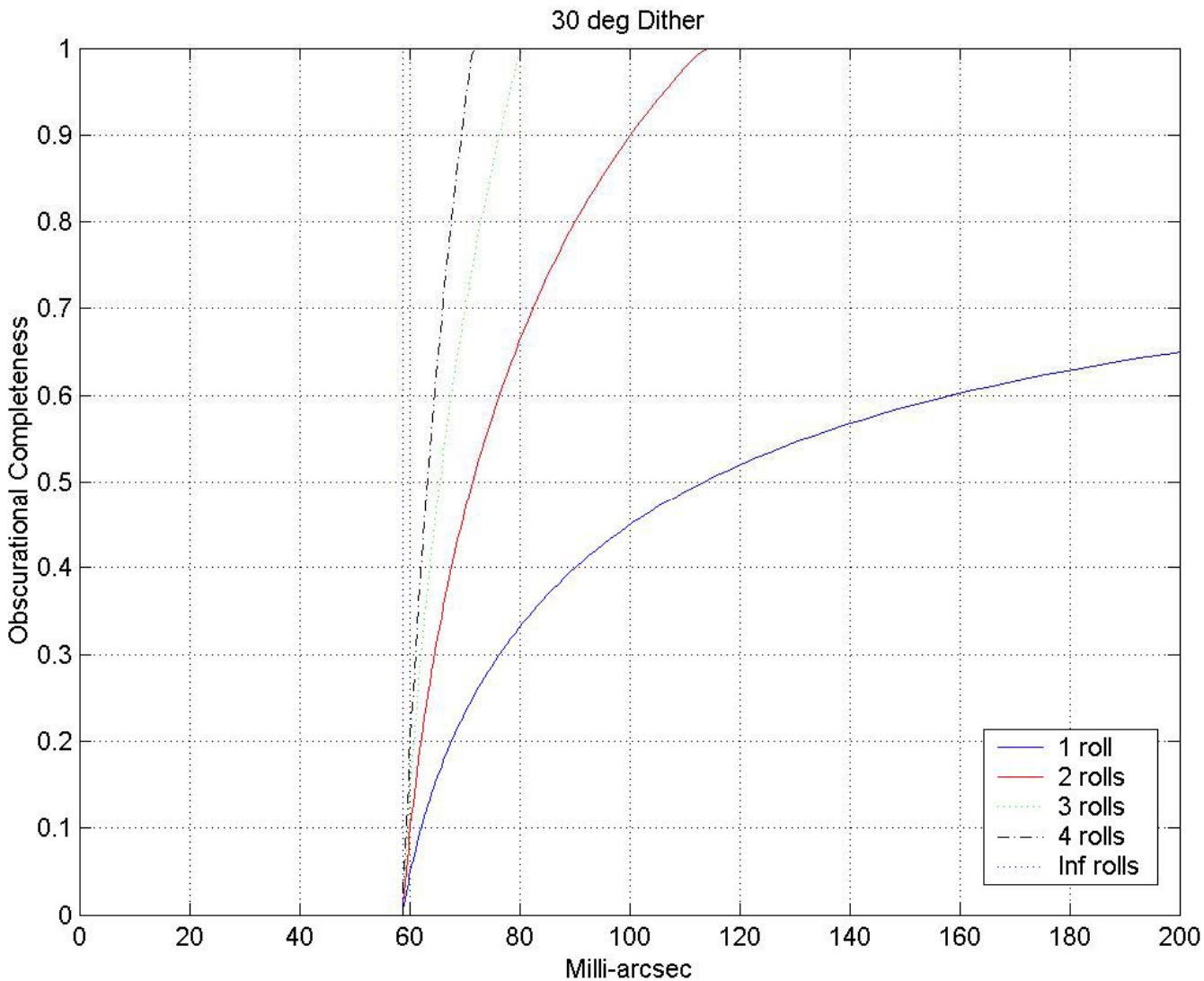


Backup Slides

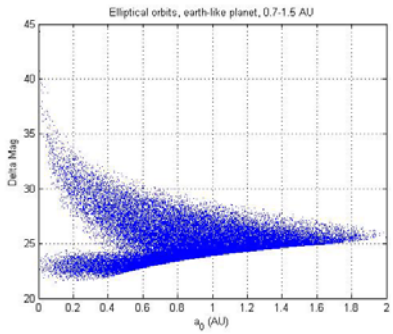
IWA – 0° dither

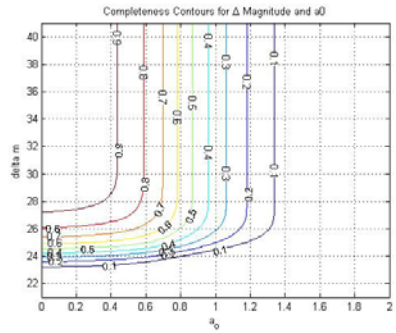

No Dither
Obscurational Completeness
Milli-arcsec
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
140
160
180
200
1 roll
2 rolls
3 rolls
4 rolls
Inf rolls

IWA - 30° dither



Completeness Summary

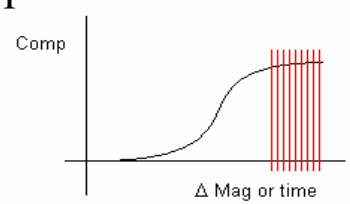




- Elliptical planetary orbits expand range of habitable planets
- Probability distribution of planets gives completeness contours
- Completeness curves are optimized for highest planet count with auction optimization

Equivalent Optimizations

JPL



Brown

	JPL		Brown	
ΔMag	# Stars	# Planets	#Stars	#Planets
25	138	32.60	135.21	32.59
25.5	125	38.29	122.77	38.32
26	115	41.10	113	40.96
27	114	42.16	106	41.04

Optimized Results at ΔMag=25 and ΔMag=26

ΔMag=25

- Planets = 25.771 (JPL)
- Planets = 26.13 (Brown)
- Participating Stars = 146
- Limited improvement over Δmag=25 cutoff

ΔMag=26

- Planets = 39.038
- Participating Stars = 126
- Great improvement over both Δmag=25 cutoff and Δmag=26 cutoff

TPF Terrestrial Planet Finder

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

Lockheed Martin
Ball Aerospace & Technologies Corp.
Northrop Grumman Space Technology
TC Technology
nightsky systems

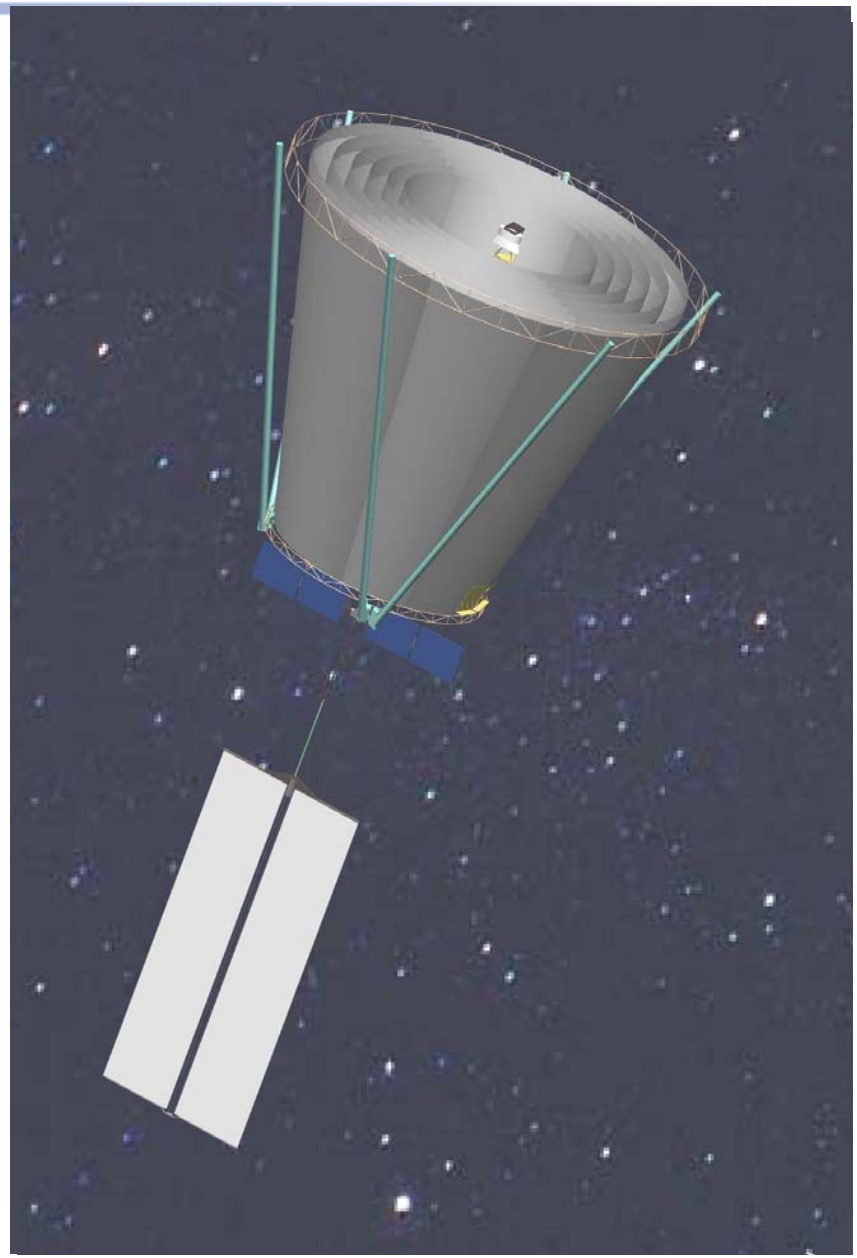
TPF Terrestrial Planet Finder

TPF-C Error Budget: Description and Plans

Stuart Shaklan

Contributors:
Luis Marchen
Joseph Green
Oliver Lay
David Palacios

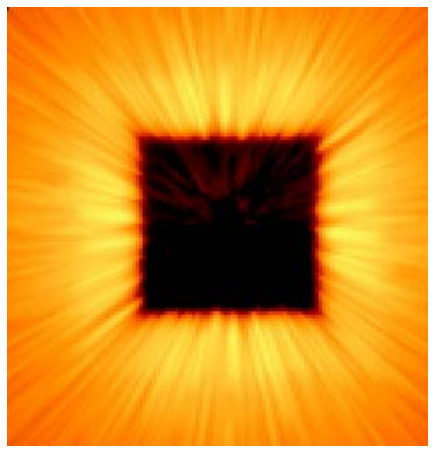
11-12 July 2005



High-Level Requirements

Table 1. TPF-Coronagraph Contrast Error Budget Requirements.

	Requirement	Comment
Static Contrast	6.00E-11	Coherent Terms
Contrast Stability	2.00E-11	Thermal + Jitter
Instrument Stray Light	1.50E-11	Incoherent light
Inner Working Angle	4 λ/D_{long}	57 mas at λ=550 nm, D_{long} = 8 m
Outer Working Angle	48 λ/D_{short}	1.5 arcsec at λ=550 nm, D_{short} = 3.5 m
Bandpass	500-800 nm	Separate observ. in three 100 nm bands.



Static and Dynamic Terms

$$\text{Contrast} = I_s + \langle I_d \rangle$$
$$\text{Stability} = \text{sqrt}(2 I_s \langle I_d \rangle + \langle I_d^2 \rangle)$$

I_s = Static Contrast	I_d = Dynamic Contrast
Wave Front Sensing Wave Front Control Gravity Sag Prediction Print Through Coating Uniformity Polarization Mask Transmission Stray Light Micrometeoroids Contamination	Pointing Stability Thermal and Jitter Motion of optics Beam Walk Aberrations Bending of optics Aberrations
Every item is unknown territory, new technology. Most are bandwidth-dependent	Solve with Design and Engineering, linear modeling. Bandwidth independent.

Error Budget Models

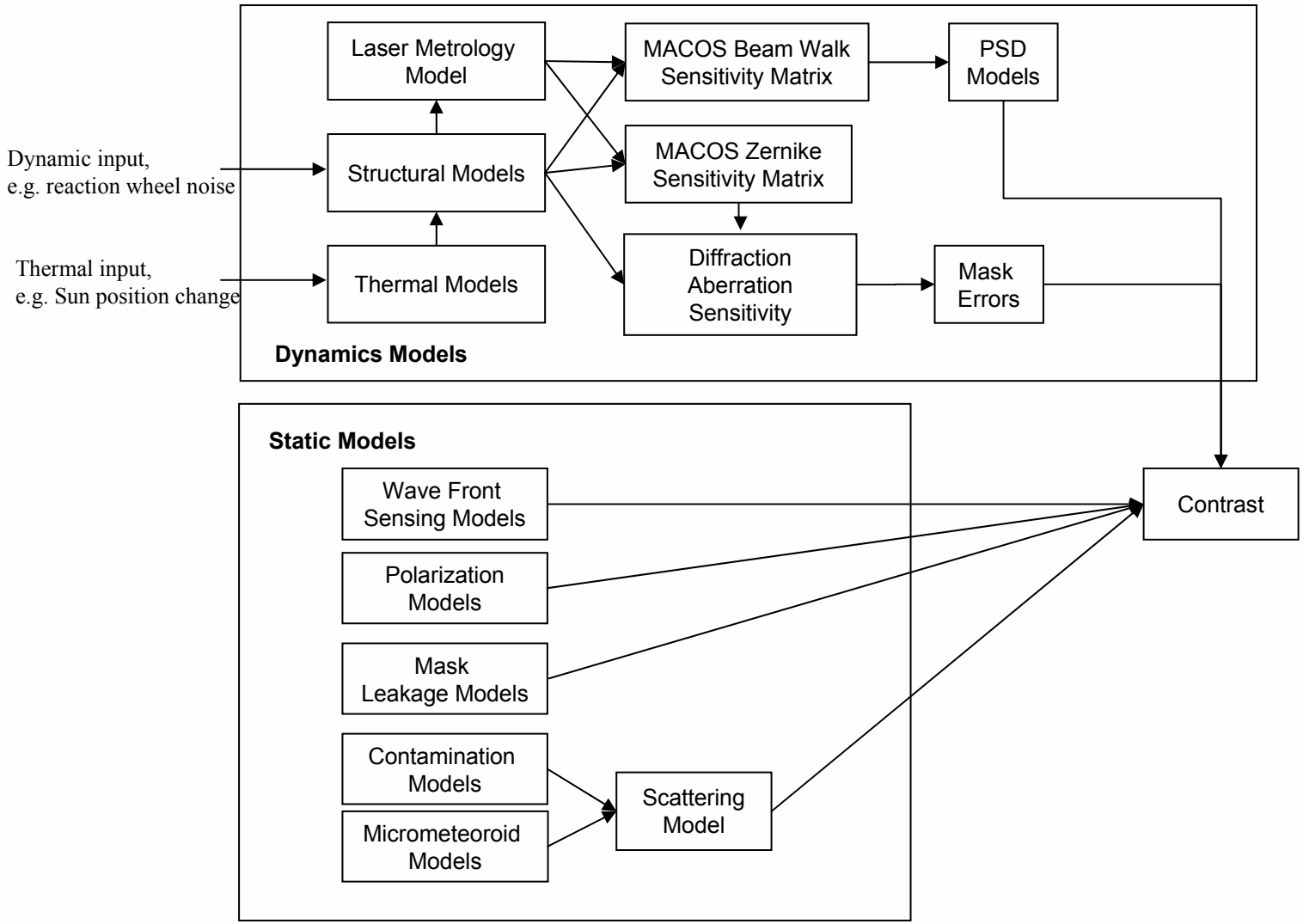


Figure 3. Models used to calculate static and dynamic contrast.

Error Budget Structure

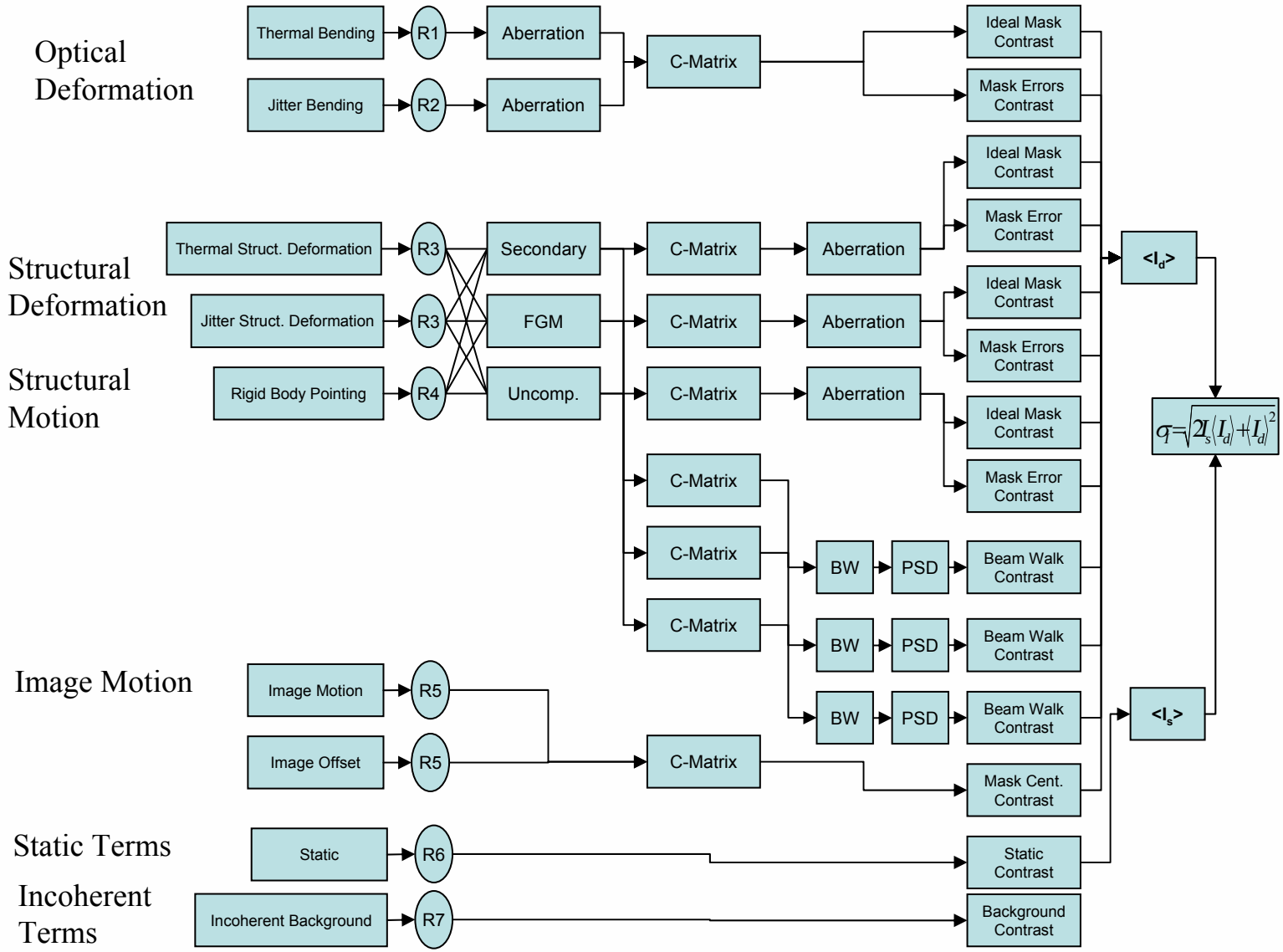
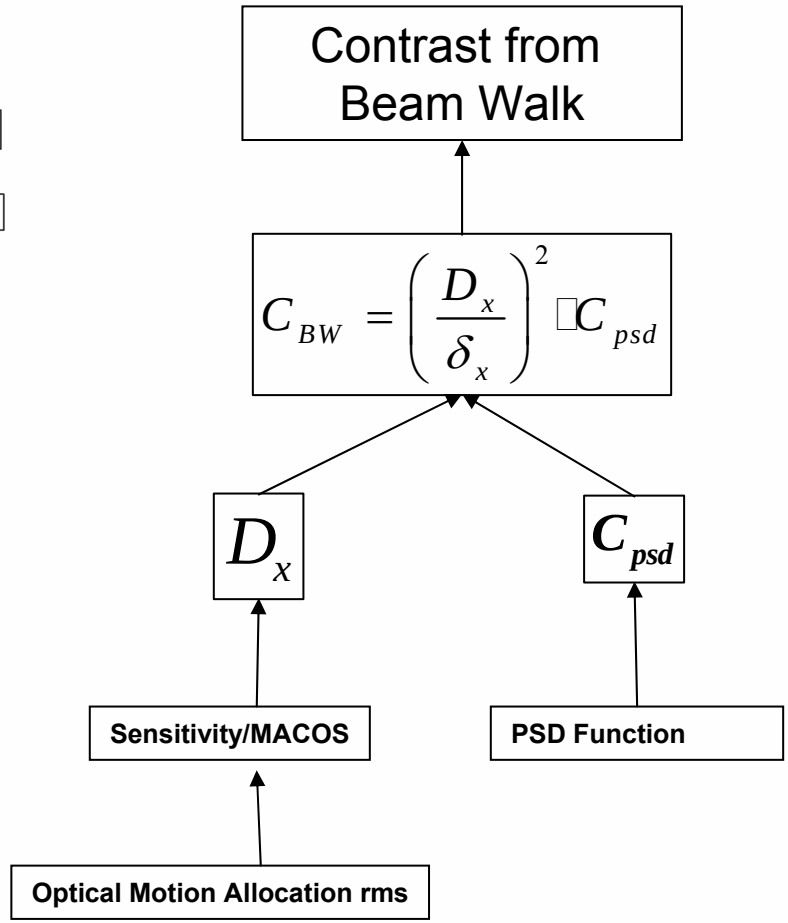


Figure 1. Error Budget Structure. 'C-matrix' is a sensitivity matrix or equation. R1-R7 are multiplicative reserve factors.

Beam Walk Model



$$C_{psd} = \left(\frac{2\pi}{\lambda} \square \sqrt{\iint 16\pi^2 (\delta_x k_x)^2 \square \left[\frac{A}{1 + \left(\frac{\sqrt{k_x^{\,2} + k_y^{\,2}}}{k_0} \right)^n} \right] dk_x dk_y} \right)^2$$

Figure 4. Beam walk calculation. C_{psd} is the contrast for a unit value of beam walk, δ_x at a spatial frequency (image plane position) of k_x.. D_x is the beam walk calculated from linear sensitivity matrices applied to allocated translation and tilt motions.

Control Systems

- 3-tiered pointing control
  - Rigid body pointing using reaction wheels or Disturbance-Free Payload
  - Secondary mirror tip/tilt (~ 1 Hz)
  - Fine-guiding mirror (several Hz)
- PM-SM Laser Metrology and Hexapod
  - Measures and compensates for thermal motion of secondary relative to primary.

Pointing Control

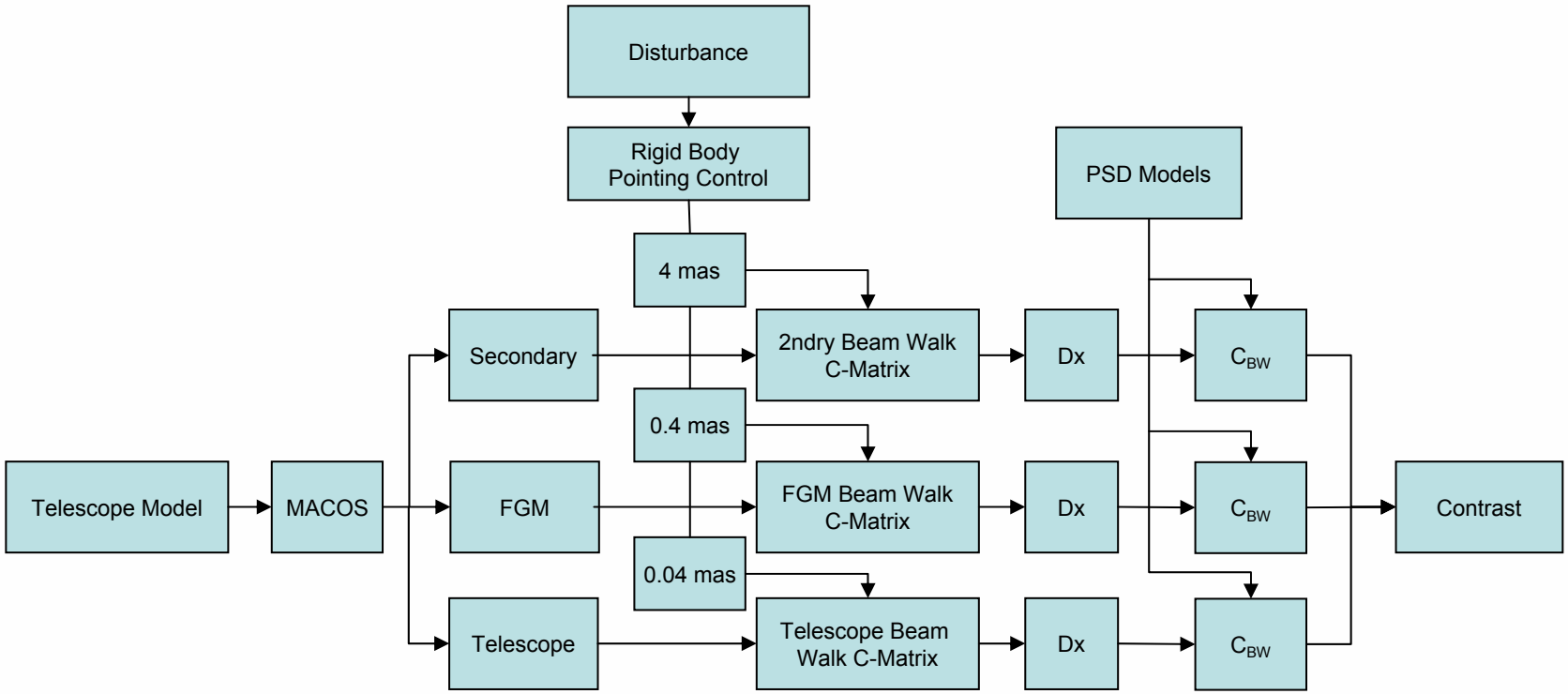


Figure 2. Pointing control. The CEB assumes a nested pointing control system. Reaction wheels and/or a Disturbance Reduction System control rigid body motions to 4 mas (1 sigma). The telescope secondary mirror tips and tilts to compensate the 4 mas motion but has a residual due to bandwidth limitation of 0.4 mas. A fine guiding mirror in the SSS likewise compensates for the 0.4 mas motion leaving 0.04 mas uncompensated.

Error Budget Screen Shot

Error Budget

		4 λ/D
Final Contrast =	WFE +Background	5.63E-11
$\sigma_I = \sqrt{2I_s\langle I_d\rangle + \langle I_d\rangle^2}$		2.00E-11
<I> = <Id> + <Is>	Total Contrast	4.13E-11
<Id> =	Jitter/Thermal Error+Bending of Optics+Rigid Body+Image Position	5.14E-12
Bending of Optics Jitter/Thermal (Includes Reserve)		1.72E-12
Jitter/Thermal Structural Deformation Aberrations and Beam Walk (Includes Reserve)		1.49E-12
Image Position Offset and Image Jitter (Includes Reserve		6.37E-13
Rigid Body Pointing (Includes Reserve)		1.29E-12
Is = Static Error (Includes Reserve)		3.62E-11
Background Error		1.50E-11

Jitter/Thermal Reserve (Beam Walk and Structural)					2.00
Reserve Factor Bending of Optics					2.00
Reserve Factor (Image Position Jitter and Offset)					2.00
Reserve Factor Mask Transmission Errors					2.00
Reserve Factor Rigid Body Pointing					2.00
Reserve Factor for WFS/C					2.00
Reserve Factor Amplitude Uniformity					2.00
Reserve Factor Polarization Leakage					2.00
FGM-Residual					0.10
Secondary-Residual					0.10
				No Reserve	Reserve
ΔM	The no reserve ΔM can be changed here			5.00E-04	1.00E-03

ON
FGM ON/OFF

ON
Secondary ON/OFF

Turn off 2ndary Mirror Pointing Control

Error Budget

		4 λ/D
Final Contrast =	WFE +Background	2.19E-10
$\sigma_I = \sqrt{2I_s\langle I_d\rangle + \langle I_d\rangle^2}$		2.00E-10
<I> = <Id> + <Is>	Total Contrast	2.04E-10
<Id> =	Jitter/Thermal Error+Bending of Optics+Rigid Body+Image Position	1.67E-10
Bending of Optics Jitter/Thermal (Includes Reserve)		1.72E-12
Jitter/Thermal Structural Deformation Aberrations and Beam Walk (Includes Reserve)		3.63E-11
Image Position Offset and Image Jitter (Includes Reserve		6.37E-13
Rigid Body Pointing (Includes Reserve)		1.29E-10
IS = Static Error (Includes Reserve)		3.62E-11
Background Error		1.50E-11

Jitter/Thermal Reserve (Beam Walk and Structural)					2.00
Reserve Factor Bending of Optics					2.00
Reserve Factor (Image Position Jitter and Offset)					2.00
Reserve Factor Mask Transmission Errors					2.00
Reserve Factor Rigid Body Pointing					2.00
Reserve Factor for WFS/C					2.00
Reserve Factor Amplitude Uniformity					2.00
Reserve Factor Polarization Leakage					2.00
FGM-Residual					0.10
Secondary-Residual					0.10
				No Reserve	Reserve
ΔM	The no reserve ΔM can be changed here			5.00E-04	1.00E-03

ON	OFF
FGM ON/OFF	Secondary ON/OFF

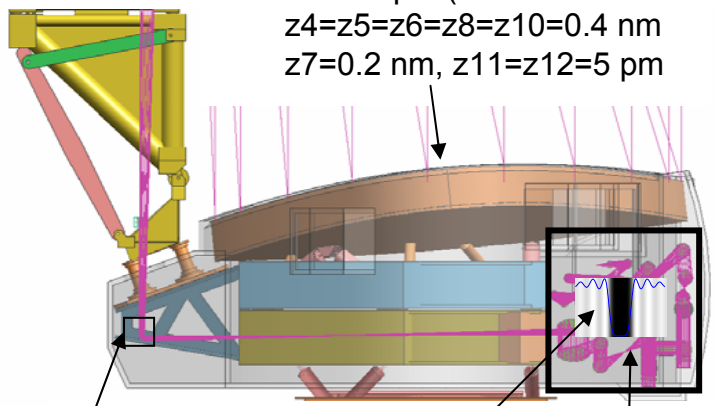
Power Spectral Density of Optics

- Fold mirrors 1 and 2 are 'super fold'
- First off-axis-parabola is 'Super OAP'
- Cylindrical mirrors are 'anamporphic'
- DM is r.s.s. of all optics. K0 is scaled value from PM (8 m scaled to 10 cm)

Table 2: PSD specifications for optics modeled in the CEB.

	Primary	Secondary	Fold	Super Fold	OAP	Super OAP	Anamorphic 1	Anamorphic 2	DM
D (m)	8.02	0.83	0.1	0.1	0.1	0.1	0.23	0.10	0.10
k0 (cy/m)	4	4	10	10	10	10	10	10	320
A (m^4)	9.60E-19	9.60E-19	1.25E-20	7.58E-21	1.25E-20	1.09E-20	5E-20	7.5E-20	8.52E-22
n	3	3	3	3	3	3	3	3	3
RMS WF	8.51E-09	9.55E-09	2.15E-09	1.67E-09	2.15E-09	2.00E-09	5.24E-09	5.27E-09	1.62E-08

Key Dynamics Requirements



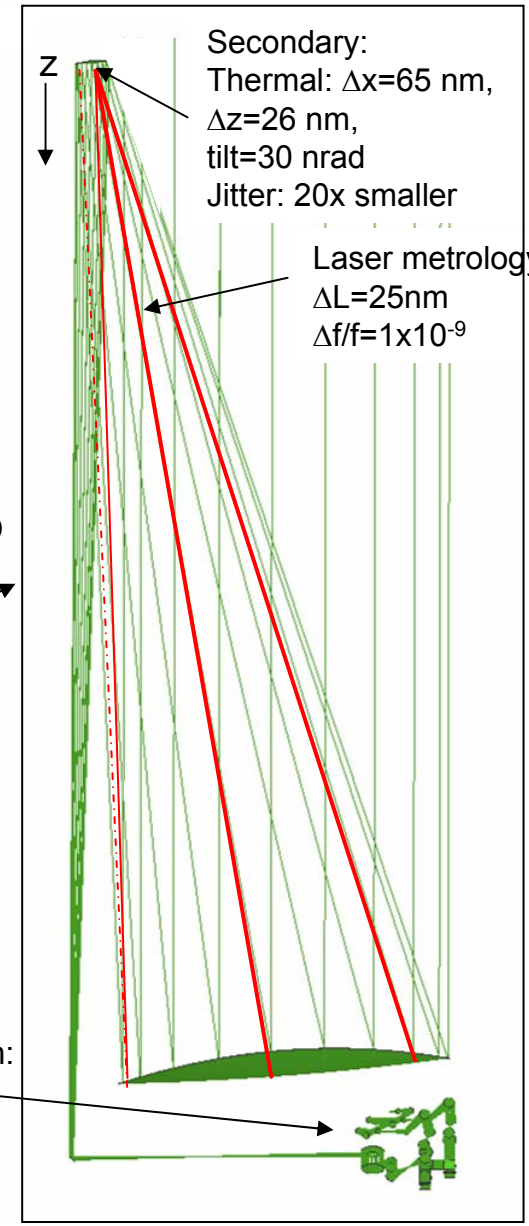
PM shape: (Thermal and Jitter)
z4=z5=z6=z8=z10=0.4 nm
z7=0.2 nm, z11=z12=5 pm

Fold mirror 1:
rms static surf =0.85nm
Thermal: 10nrad, 100 nm
Jitter: 10 nrad, 10 nm

Mask centration:
offset=0.3 mas
amplitude=0.3mas

Mask error =
5e-4 at 4 λ/D

4 mas rigid
body
pointing



Secondary:
Thermal: Δx=65 nm,
Δz=26 nm,
tilt=30 nrad
Jitter: 20x smaller

Laser metrology:
ΔL=25nm
$\Delta f/f=1\times10^{-9}$

Coronagraph optics motion:
Thermal:10nrad, 100nm
Jitter: 10 nrad, 10 nm

Figure 5. We identify the major engineering requirements to meet the dynamic error budget. Thermally induced translations lead to beam walk that is partially compensated by the secondary mirror. Jitter is partially compensated by the fine guiding mirror.

Contrast Roll Up

Table 4: Rolled up Dynamic Contrast Contributors

Perturbation	Contributor	Nature	Contrast	Fraction
Structural Defomation	Beam Walk	Thermal	8.29E-13	16.12%
		Jitter	6.33E-13	12.31%
	Aberrations	Thermal	3.28E-14	0.64%
		Jitter	4.43E-17	0.00%
Bending of Optics	Aberrations	Thermal	8.60E-13	16.72%
		Jitter	8.60E-13	16.72%
Pointing	Beam Walk		1.29E-12	25.10%
	Image Motion		9.04E-14	1.76%
	Mask Error		5.46E-13	10.63%
SUM			5.14E-12	

Contrast and Contrast Stability

Error Budget

		4 λ/D
Final Contrast =	**WFE +Background**	**5.63E-11**
$\sigma_I = \sqrt{2I_s\langle I_d\rangle + \langle I_d\rangle^2}$		**2.00E-11** ←
<I> = <Id> + <Is>	**Total Contrast**	**4.13E-11**
<Id> =	**Jitter/Thermal Error+Bending of Optics+Rigid Body+Image Position**	**5.14E-12** ←
Bending of Optics Jitter/Thermal (Includes Reserve)		**1.72E-12**
Jitter/Thermal Structural Deformation Aberrations and Beam Walk (Includes Reserve)		**1.49E-12**
Image Position Offset and Image Jitter (Includes Reserve		**6.37E-13**
Rigid Body Pointing (Includes Reserve)		**1.29E-12**
IS = Static Error (Includes Reserve)		**3.62E-11** ←
Background Error		**1.50E-11**

Jitter/Thermal Reserve (Beam Walk and Structural)					2.00
Reserve Factor Bending of Optics					2.00
Reserve Factor (Image Position Jitter and Offset)					2.00
Reserve Factor Mask Transmission Errors					2.00
Reserve Factor Rigid Body Pointing					2.00
Reserve Factor for WFS/C					2.00
Reserve Factor Amplitude Uniformity					2.00
Reserve Factor Polarization Leakage					2.00
FGM-Residual					0.10
Secondary-Residual					0.10
				No Reserve	Reserve
ΔM	**The no reserve ΔM can be changed here**			5.00E-04	1.00E-03

ON	ON
FGM ON/OFF	Secondary ON/OFF

Static Terms: Work in Progress

- SPIE 5905, San Diego August 2005
  - "Coronagraph Mask Tolerances For Exo-Earth Detection," Oliver Lay et al.
    - Broad band limitations in binary mask design, 2-DM control
  - "Measurement of Wavefront Phase Delay and Optical Density in Apodized Coronagrapic Mask Materials," P. Halverson et al.
    - HEBS masks, broad band response
  - "Polarization-Compensating Protective Coatings for TPF-Coronagraph Optics to Control Contrast Degrading Cross-Polarization Leakage" K. Balasubramanian et al.
    - Broad-band polarization control

Plans

- Re-evaluate requirements
  - Set limiting_delta_magnitude = 26?
  - 2-3x change in structural stability requirements
- Static Error Budget
  - Broad-band limitations
  - Gravity Sag
  - Chromatic Mask Errors
  - Mask Polarization Effects
- Incoherent Light
  - Stray light study underway at GSFC (Ed Frenier)
- Dynamic Error Budget
  - Re-allocate to match modeling results
- Detection vs. Characterization
  - Same structure, but characterization requirements may be more challenging because spectral line depth is small (signal contrast << 1E-10).

LOCKHEED MARTIN
Ball Aerospace & Technologies Corp.
NORTHROP GRUMMAN Space Technology
TC Technology
nightsky systems

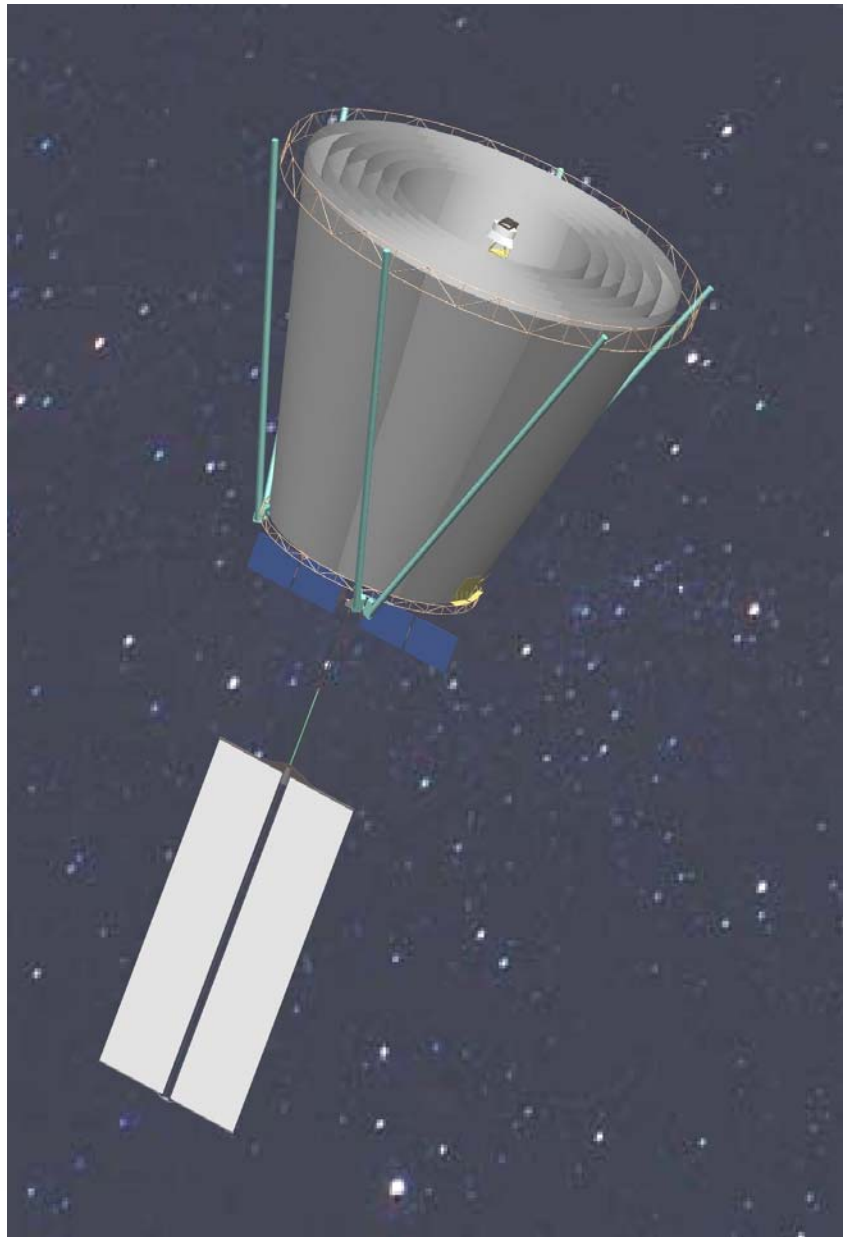
TPF Terrestrial Planet Finder

OTA and Starlight Suppression System

Zakos Mouroulis

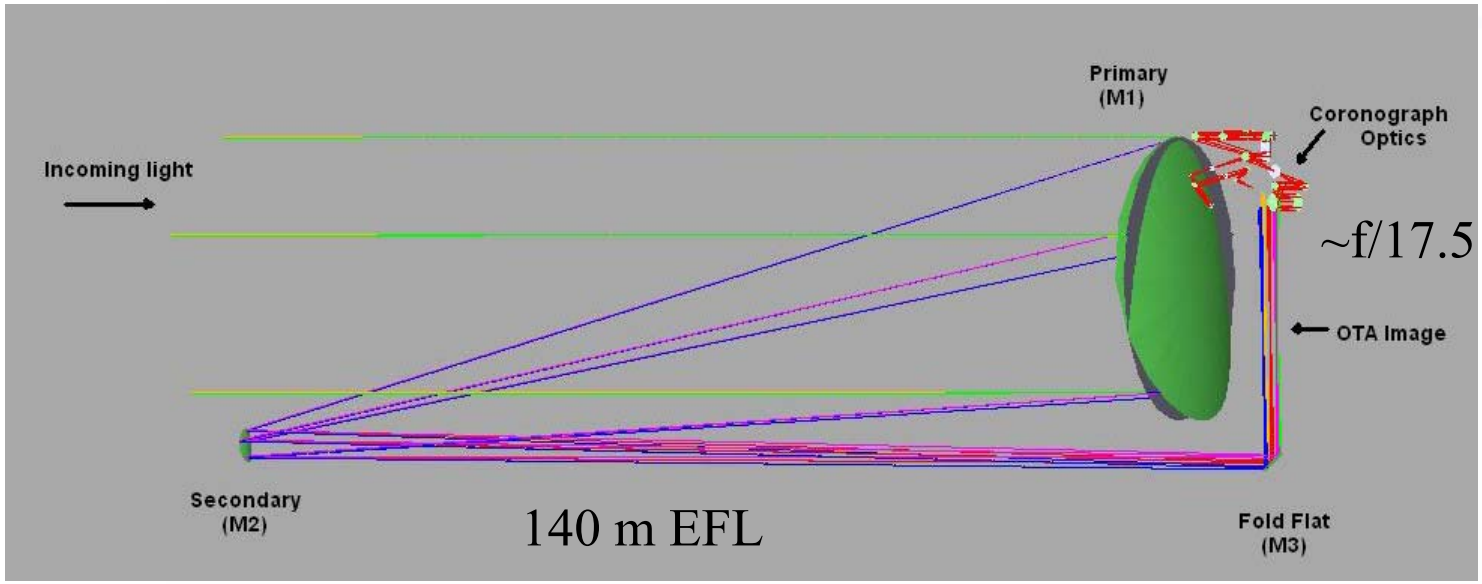
Contributors:
Ray Ohl
Stuart Shaklan
Joe Green
Bala Balasubramanian

11-12 July 2005



OTA optical concept

Perspective view of ray trace (~YZ plane) showing off-axis direction

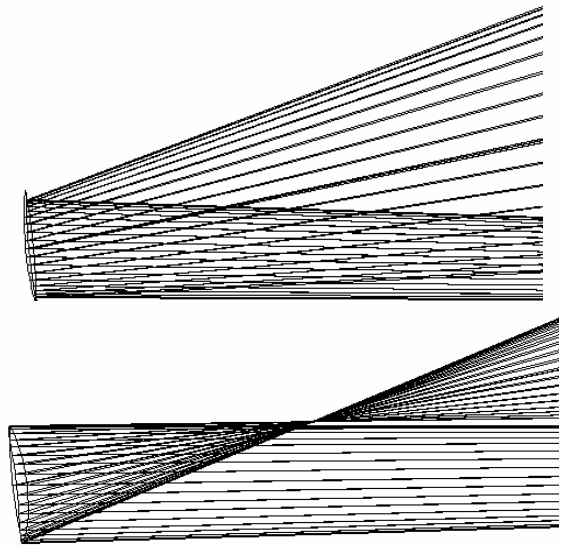


Name	Physical size		Off-axis distance (mm)	R (mm), f/#	k
	X (mm)	Y (mm)			
PM	8000	3500	2300	26750, 3.82	-1.00189
SM (convex)	890	425	237	3041, 4.13	-1.49
M3	290	310		:	

- Ritchey-Chrétien telescope
- 2 powered mirrors (PM, SM) and 1 flat (M3)
- PM and SM are hyperbolic, SM is convex
- Curved focal surface
- Off-axis aperture (in YZ plane)
- Astigmatism is the primary off-axis aberration
- Coating: protected silver

On-going trade studies

- Optical prescription: Gregorian vs. ~Cassegrain
  - Alignment sensitivities
  - Polarization
  - Stray light
  - Convex mirror fabrication/testing
  - Packaging
  - OTA wavefront correction

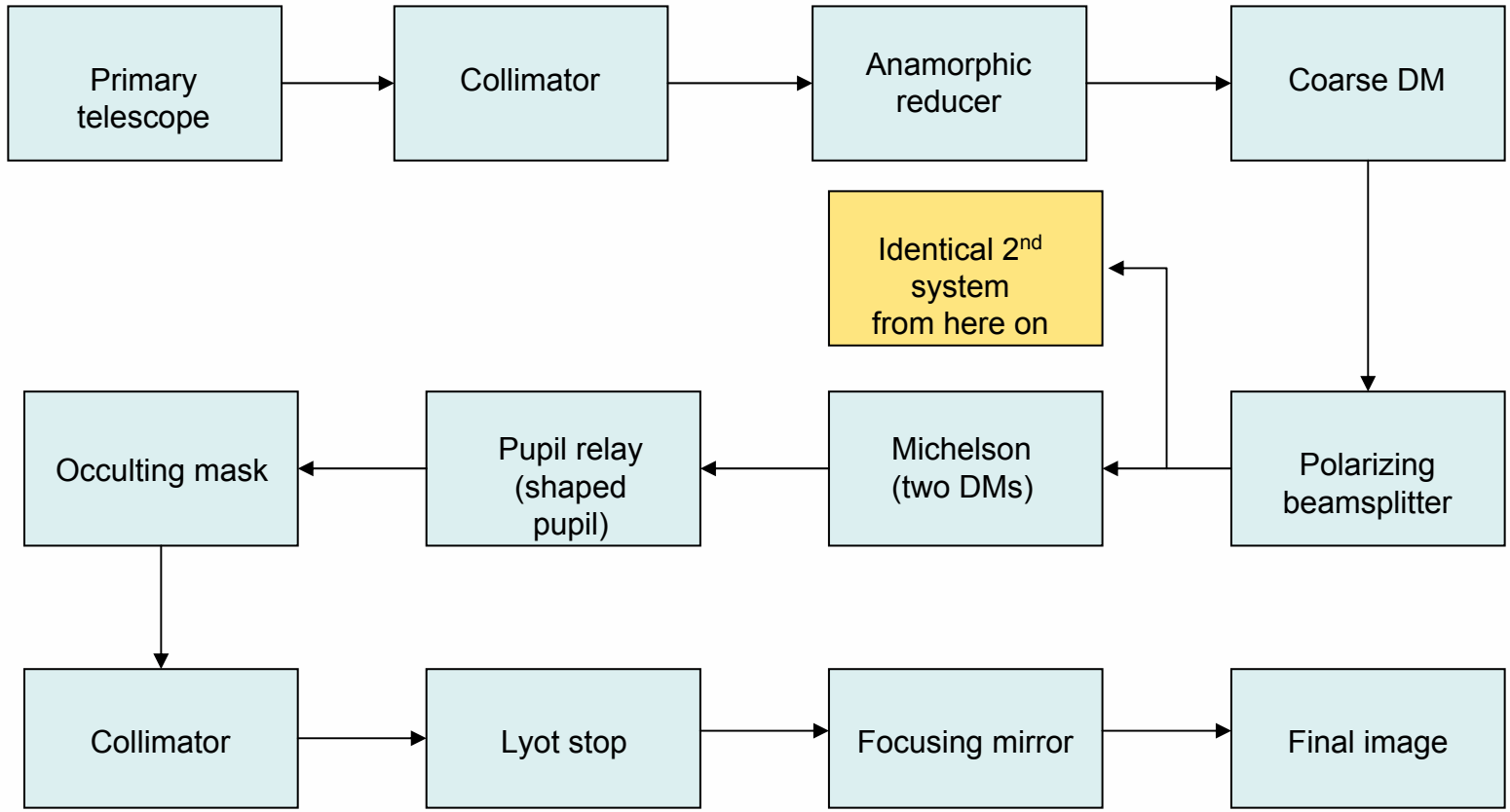


- PM mirror design
  - Blank material: Zerodur (Schott) vs. ULE (Corning)
  - OTA wavefront correction: PM actuators vs. "coarse DM" in coronagraph
  - Open-back vs. closed-back optimized blank

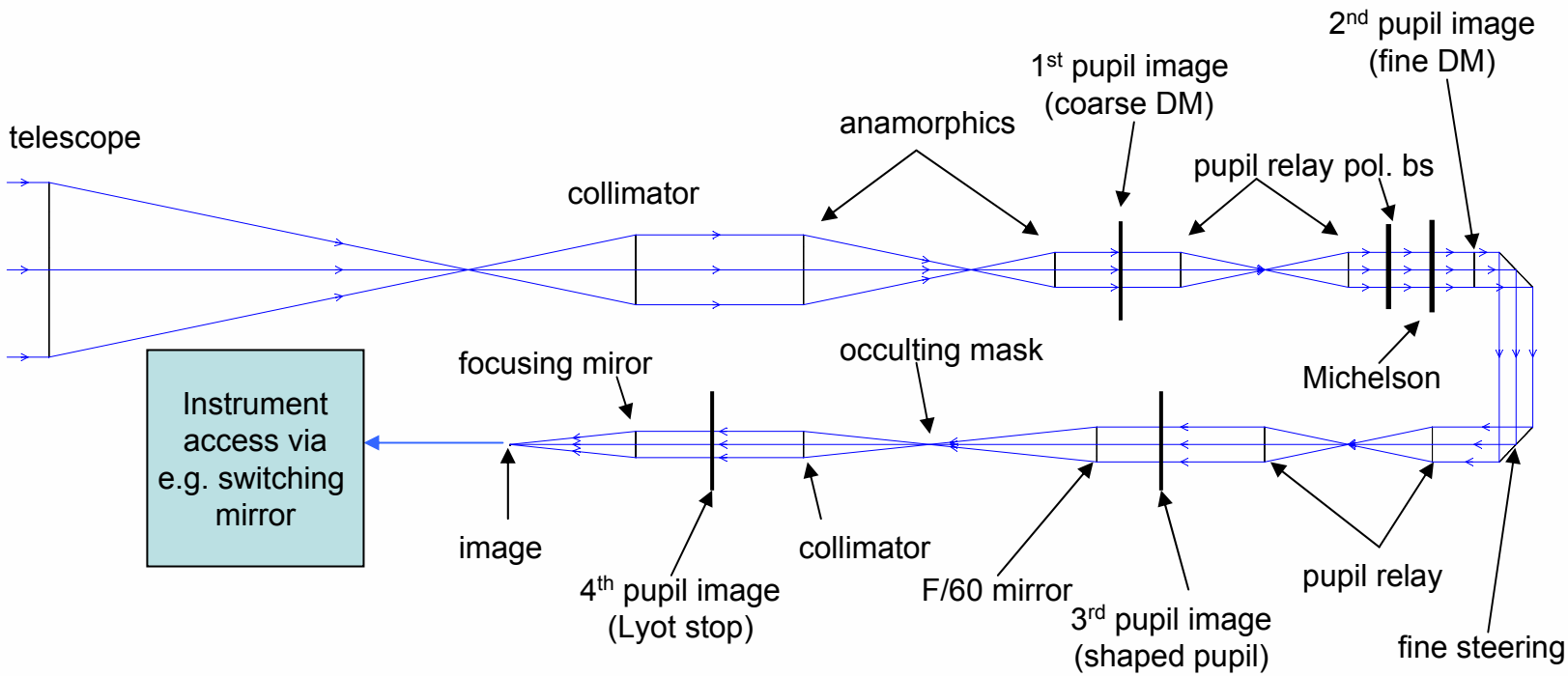
Starlight Suppression System

- "Expanded" Lyot coronagraph, with four pupil locations: coarse DM, fine DM, shaped pupil, Lyot mask
- Anamorphic optics provide circular beam cross section onto coarse DM and beyond
- Polarizing beamsplitter arrangement provides two distinct coronagraphs (paths)
- Two fine DMs per path in a Michelson arrangement for amplitude and phase correction
- System comprises only collimating and focusing mirrors, with aberrations corrected everywhere along the optical train at the level of ~0.001λ
- Options under consideration include removing polarizing elements and also possibly the Michelson, leading towards an all-reflective, single path system

System Block Diagram

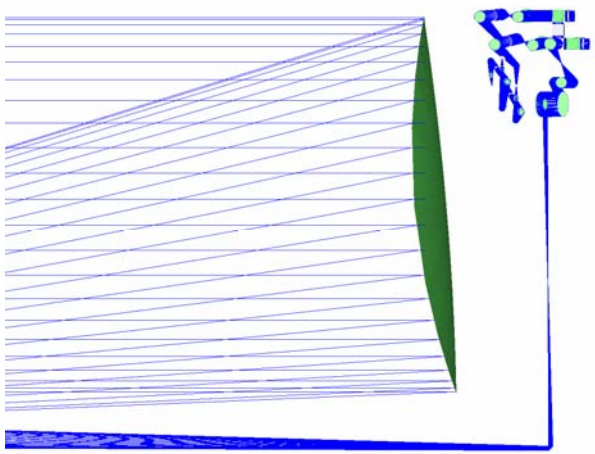


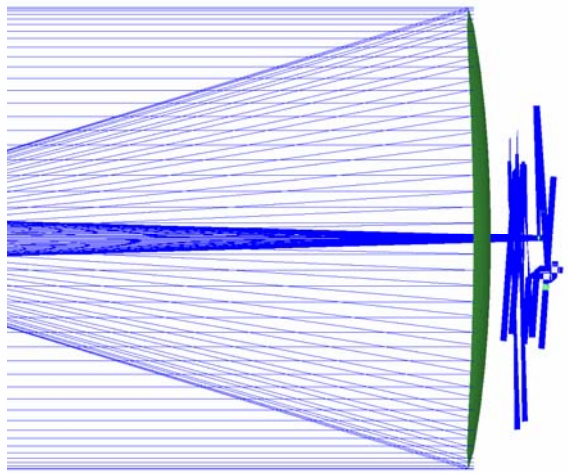
System Schematic

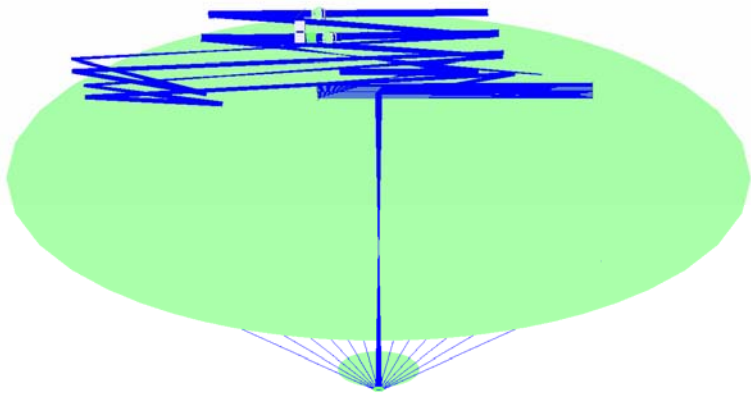


- shows the number of pupil locations, intermediate foci, collimated spaces
- not all optical elements identified
- beam diameters & focal lengths not to scale
- mirrors shown as perfect lenses

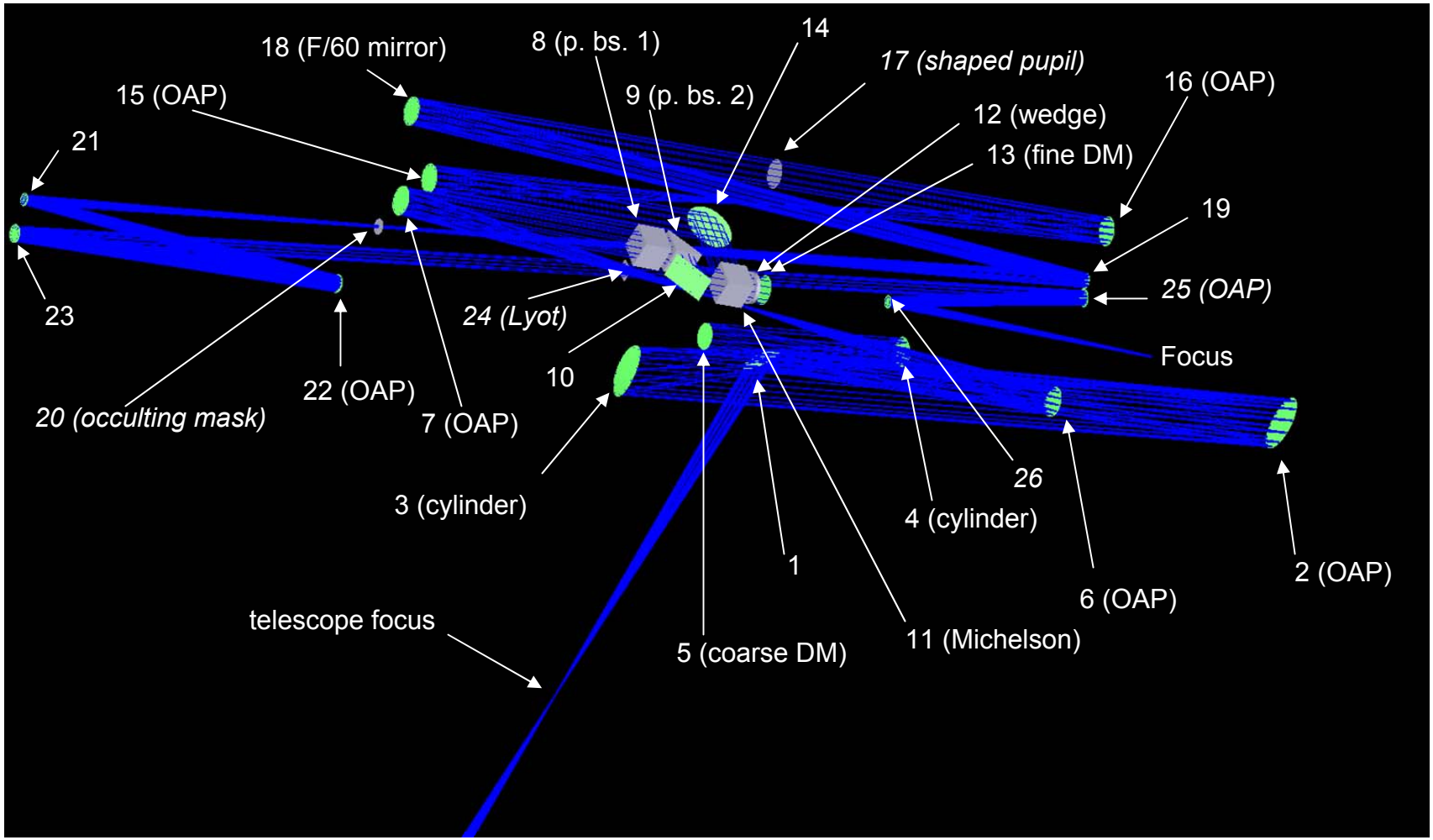
Three views of the SSS accommodation behind the telescope primary





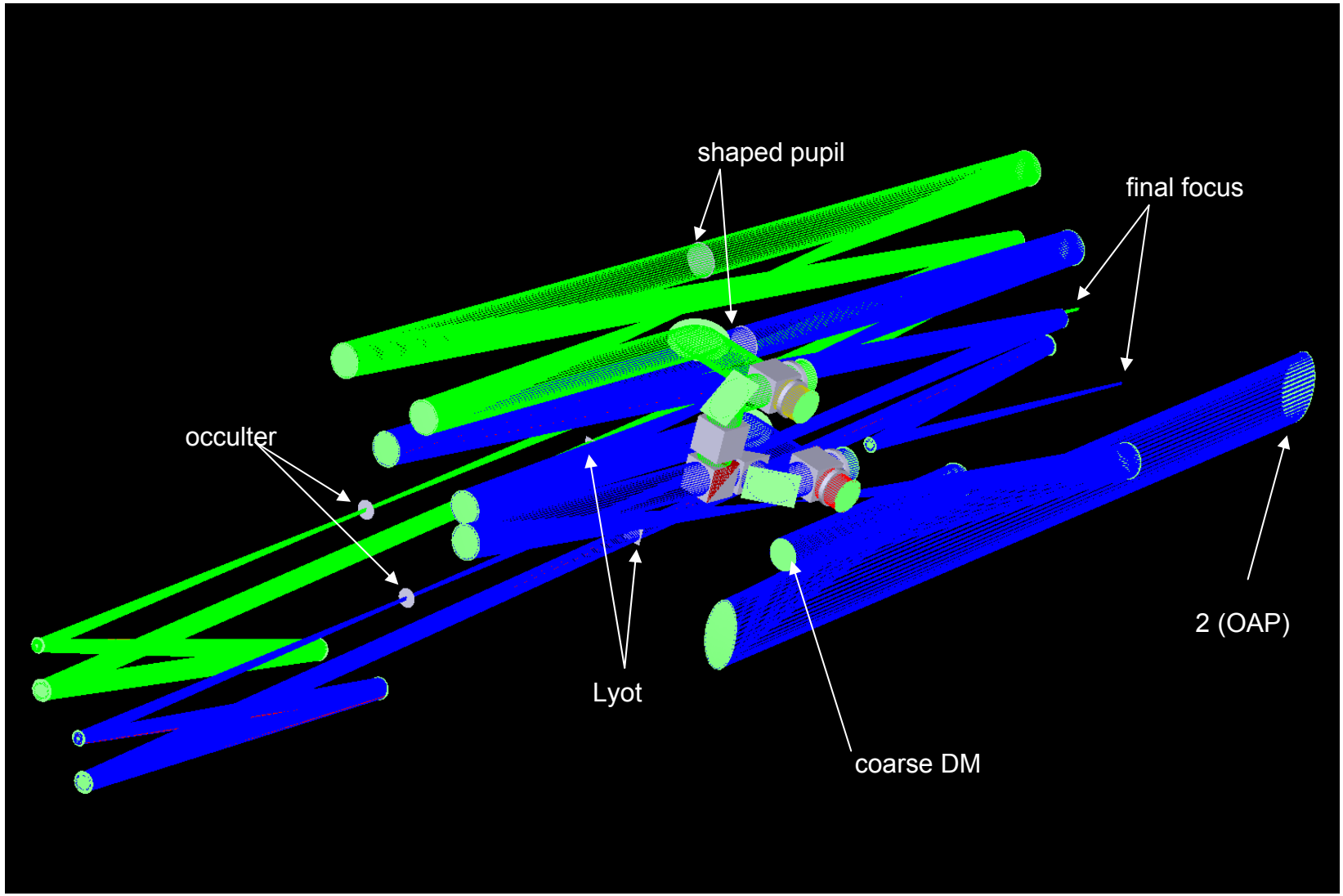


Optical layout (single path)



All powered mirrors are off-axis parabolas (OAP). Elements not otherwise identified are flat fold mirrors. Numbering of elements follows the light (same as table on p. 7.)
Shows one polarization path and a single path through the Michelson (one fine DM).

Optical layout (all paths)



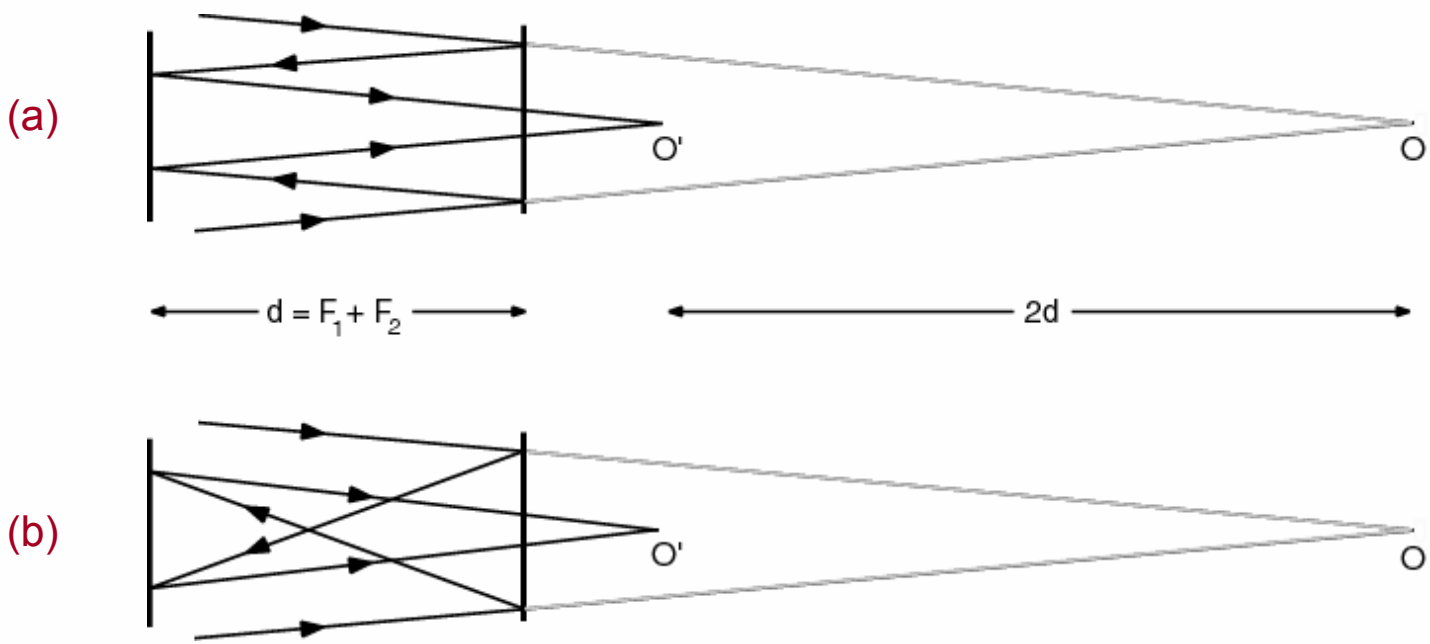
Shows both polarizations and two fine DMs per path (complete Michelson arrangement)
Second polarization path shown in green. Starts at element #2 of previous slide.

Element listing

Element #	Type	Focal length (mm)	Approx. beam footprint (mm)	Function
1	Flat mirror		140x46	Fold
2	Parabolic mirror	4000	230x100	Collimator
3	Cylindrical mirror	800	230x100	Anamorphic reducer (1)
4	Cylindrical mirror	350	100 Ø	Anamorphic reducer (2)
5	Deformable mirror		100 Ø	***Coarse DM***
6	Parabolic mirror	1500	100 Ø	Pupil relay (1)
7	Parabolic mirror	1500	100 Ø	Pupil relay (2)
8	Polarizing beamsplitter (1)		100 Ø	Separates polarizations
9	Polarizing beamsplitter (2)		100 Ø	Increases unwanted beam extinction
10	Flat mirror		140x100	Fold/fine steering
11	Beamsplitter		100 Ø	Michelson
12	Wedge		100 Ø	Chromatic correction
13	Deformable mirror		100 Ø	***Fine DM***
12	Wedge		100 Ø	Same as 12(return path)
11	Beamsplitter		100 Ø	Michelson (return path)
14	Flat mirror		100x140	Fold/fine steering
15	Parabolic mirror	1500	100 Ø	Pupil relay (1)
16	Parabolic mirror	1500	100 Ø	Pupil relay (2)
17	Optional mask		100 Ø	***Shaped Pupil***
18	Parabolic mirror	6000	100 Ø	F/60 to occulting mask
19	Flat mirror		56 Ø	Fold
20	Mask			***Occulting mask***
21	Flat mirror		35x30	Fold
22	Parabolic mirror	3000	55x60	Collimator
23	Flat mirror		52 Ø	Fold
24	Stop		50 Ø	***Lyot stop***
25	Parabolic mirror	2000	52 Ø	Focusing
26	Flat mirror		35x32	Fold
27				Final focus

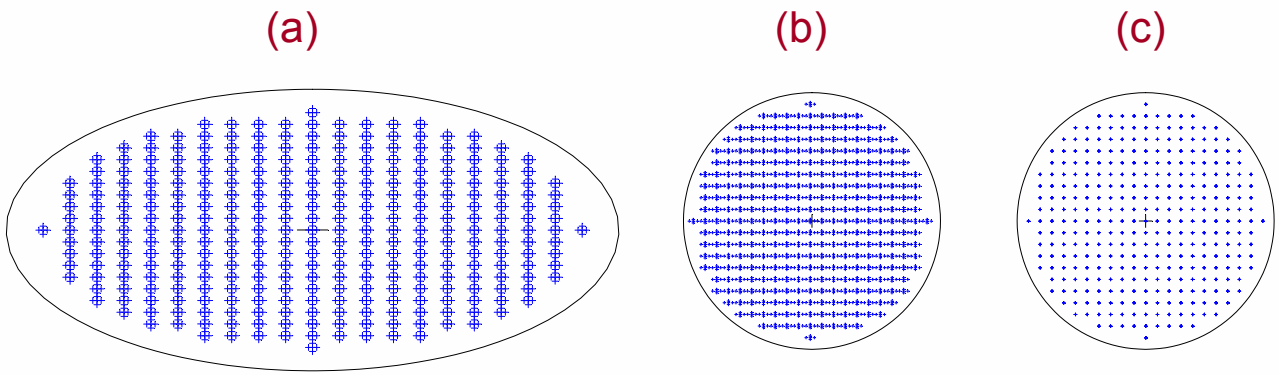
Principle of the anamorphic reducer

(a): non-imaging direction (b): imaging direction



Original pupil image is at O. After insertion of reducer, it is imaged at O' for both directions. Shown here with ideal thin mirrors. In (a) rays appear to follow the law of reflection since the mirror has no power. In (b), the mirror has power.

Effect of the anamorphic reducer



Beam footprints at (a): first cylindrical mirror, (b) second cylindrical mirror, (c) coarse DM

Each dot in (c) represents ray intersections from all field points, which are closely coincident, indicating good pupil imagery. In (a) and (b) which are far from a pupil location, the ray intersections are smeared forming a near continuum.

Polarizing beamsplitter approach

Crystal:

- High extinction and broadband well beyond 1000 nm
- Serious aperture size restriction (<~2") necessitates re-imaging to 4" DM
- Cannot be polished well enough at arbitrary angles
- Not optimum for constructing wedges

(Not feasible)

Thin film:

- Not high extinction, needs extra polarizer (or 2nd cube)
- A lot of glass, requires extreme control of optical quality
- Can be made to size
- Sufficiently broadband for 500-800 nm, very challenging (impossible?) beyond
- Can make arbitrary wedge angles easily for controlling chromatic shift

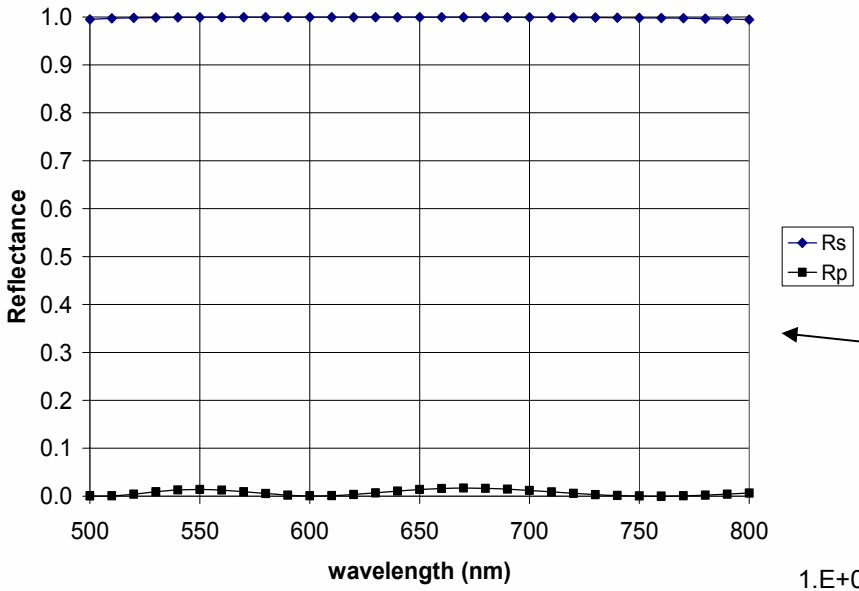
(Baseline)

Wire grid:

- Not high extinction, needs two in series
- Sufficiently broadband, even to 1000 nm
- Can be made on high quality fused silica substrates
- Can make arbitrary wedge angles
- Not yet demonstrated at large sizes needed

(probably best future approach as technology matures)

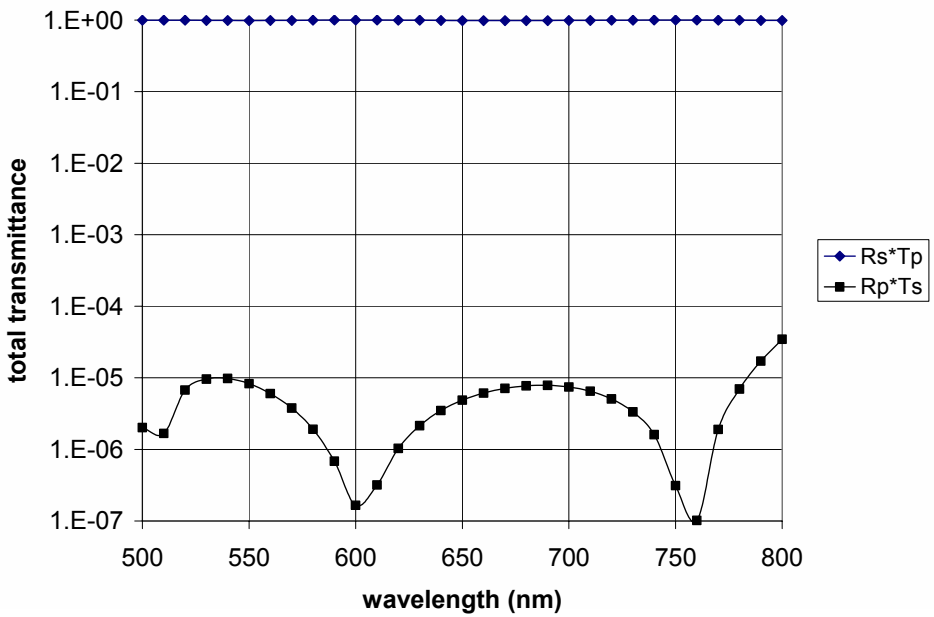
Polarizing beamsplitter performance



Based on a preliminary 10-layer MgF_2/TiO_2 design sandwiched in LaK glass.

s and p reflectances for a single cube

Transmittance of two crossed cubes. Top curve has a minimum value of 98.3%. Leakage component is below 1e-4 throughout.



Polarizing beamsplitter design

"Cubes" are quasi-cubes to avoid ghosts:

surface	*Angle (deg)*
front	-0.2
rear	0.2
air gap	0.6
last	0.4

- First cube wedge: -0.2°, second cube wedge 0.4°
- Air gap compensates for wedge fabrication error.

Chromatic compensation (through two pol. bs quasi-cubes):

Angular displacement: << 1 nrad

Linear displacement: ~0.1 μm

These angles are semi-arbitrary, compensation can be achieved with any (small) initial angle.

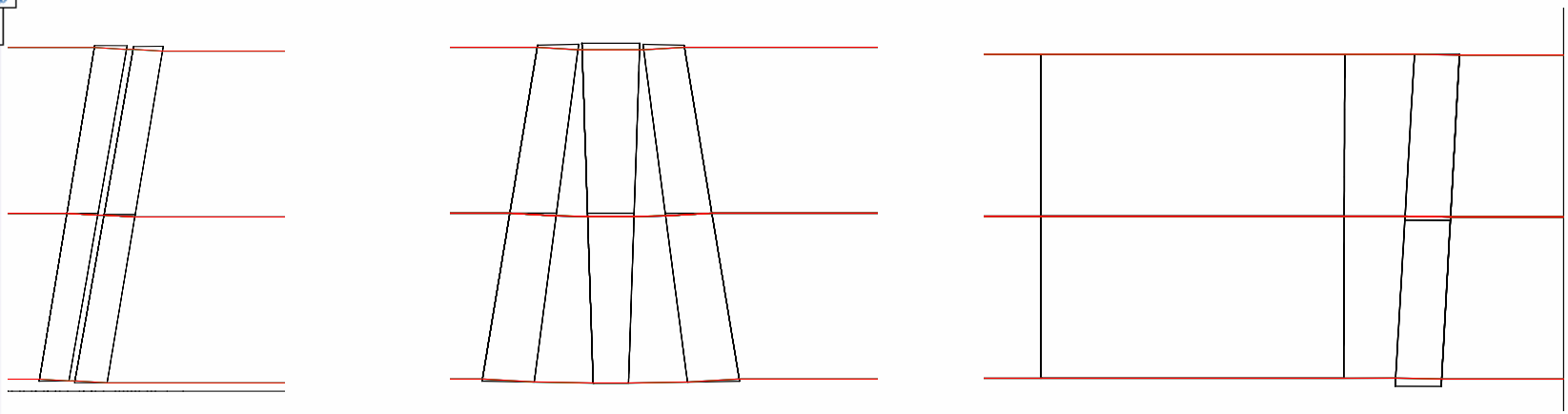
If wire grid polarizers prove to be a better solution, chromatic compensation can be achieved in different ways (next).

Michelson vs. Mach Zehnder for DM arrangement

Choice is driven primarily by wedge (beamsplitter) design and compactness

M-Z

Compensating wedge options



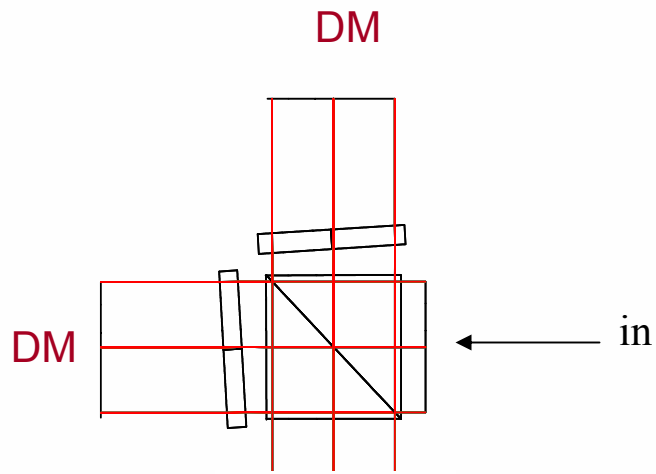
Double wedge
(1st surface refl.)

Triple wedge
(1st surface refl.)

Quasi-cube plus wedge
(immersed reflection, 45°)

	Double wedge	***Triple wedge***	***Quasi-cube***
Linear dispersion	27 μm	0.1 μm	6 μm
Angular dispersion	<< 1 nrad	0.8 nrad	<< 1 nrad

Michelson with quasi-cube plus wedge chosen

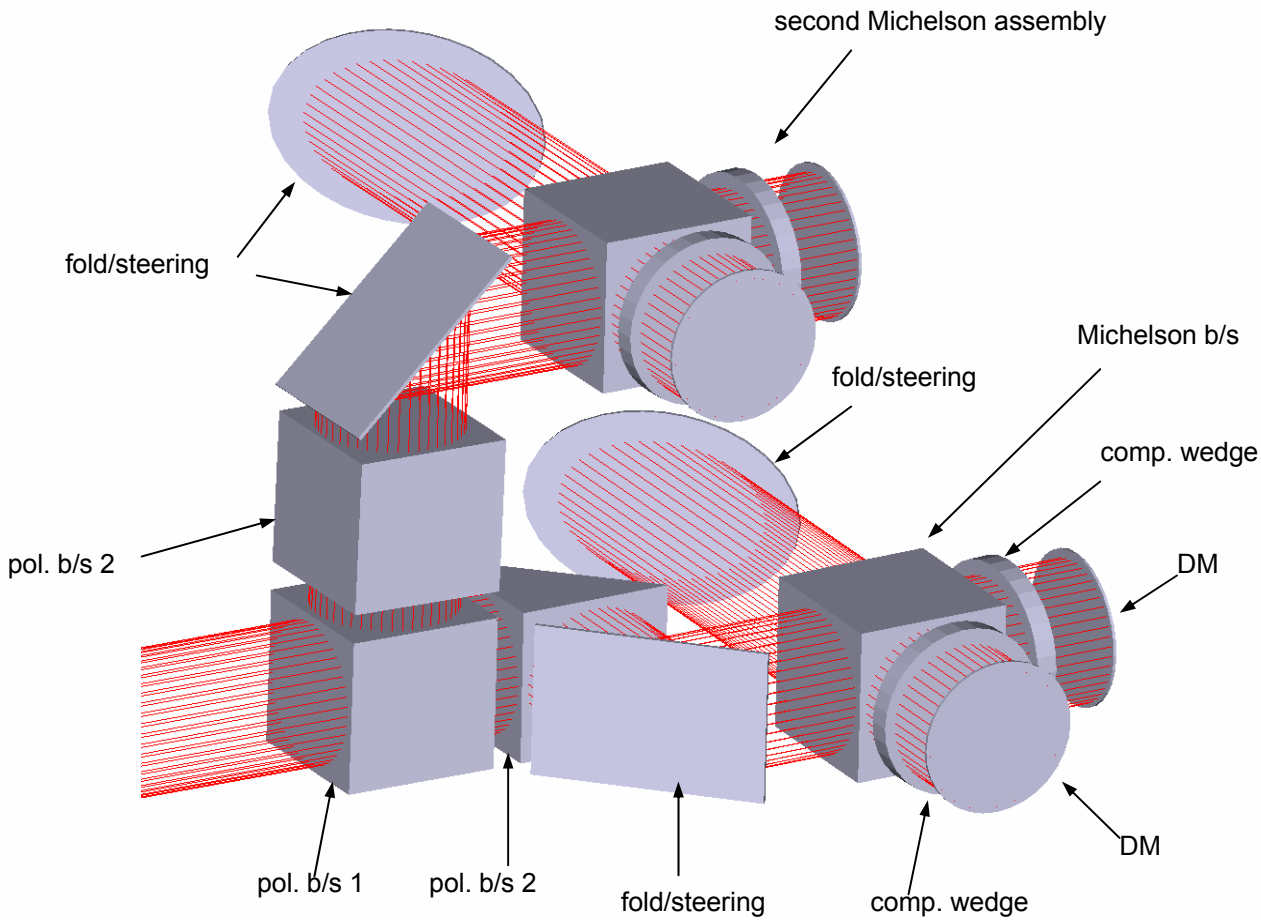


Cube and prism have wedge angles of 0.2°, “air” gap has a wedge angle of ~3.3°.

Material is fused silica

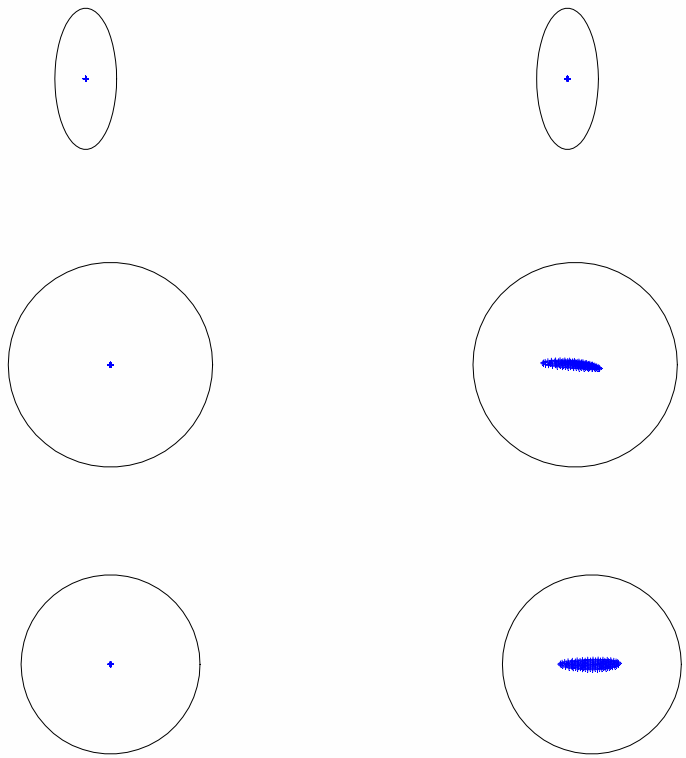
Symmetric design

Complete pol. b/s and Michelson assembly



Design performance

Spot diagrams shown inside the corresponding Airy disk size for the middle of the field and the worst-case 2” field location.



Telescope focus

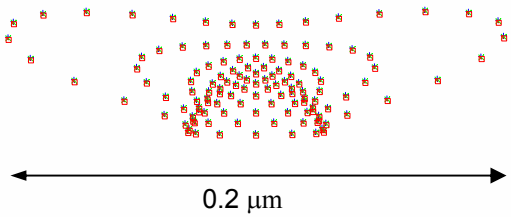
Occulting mask

Final focus

Center of field has only telescope residual aberration. Edge of field gradually degrades as more OAPs are added along the way.

Design performance

	Field position	Strehl ratio	rms aberration (waves @ 500 nm))
Telescope focus	center	1.000	0.0001
	2”	1.000	0.0004
Occulting mask	center	1.000	0.0001
	2”	0.986	0.0145
Final focus	center	1.000	0.0001
	2”	0.974	0.0295



Magnified polychromatic spot diagram at final focus shows chromatic error fully suppressed.

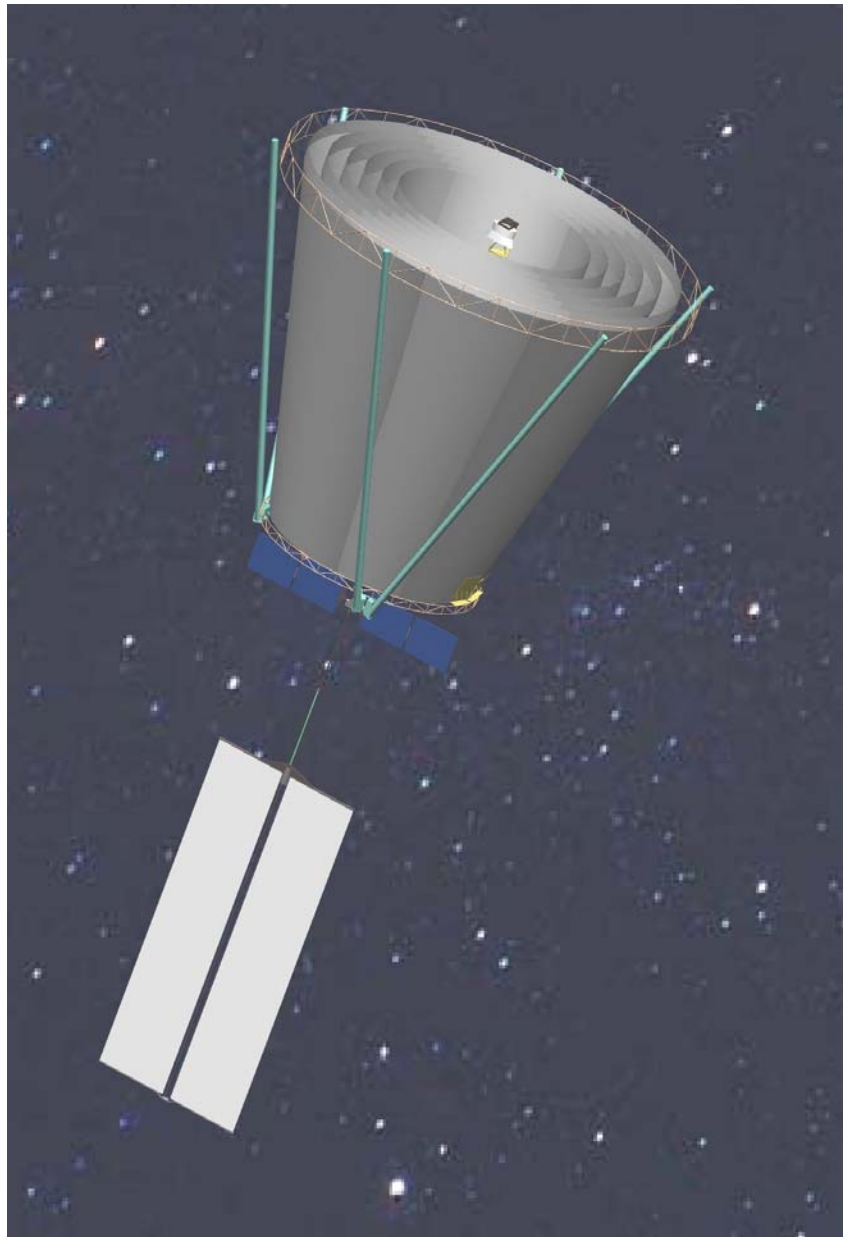
LOCKHEED MARTIN
Ball Aerospace & Technologies Corp.
NORTHROP GRUMMAN Space Technology
TC Technology
nightsky systems

TPF Terrestrial Planet Finder

System Pointing Control Architecture & Design

James Alexander

Contributors:
Alice Liu (GSFC)
Carl Blaurock (Nightsky Systems)
Larry Dewell (LMCO)



11-12 July 2005

Outline

- Pointing Control System (PCS) Overview
  - Objectives
  - Vibration isolation architectures
  - Requirements
  - Operational modes
- Pointing Control System Design
  - Actuator description
  - Sensor descriptions

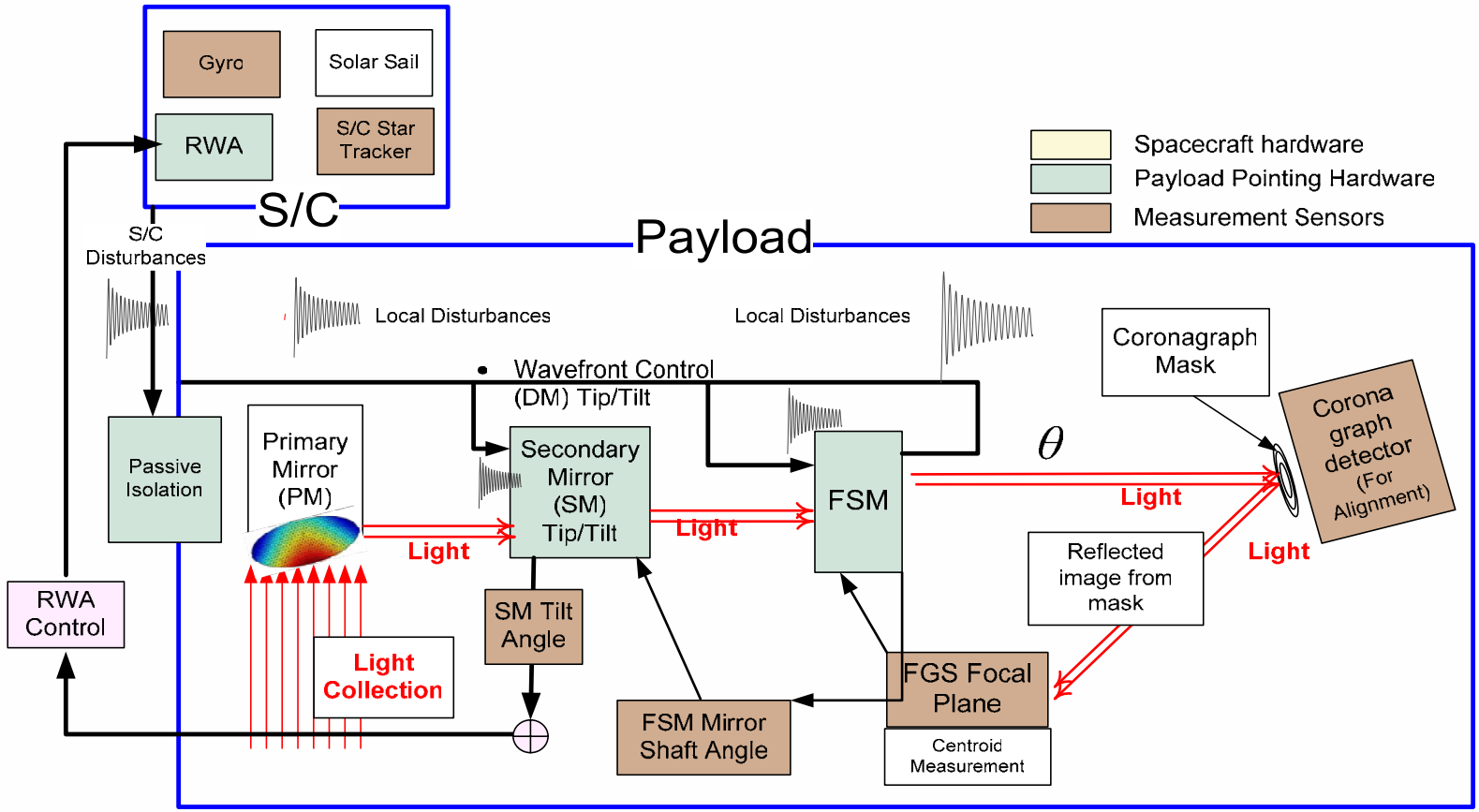
Flight Baseline 1 Design Objectives

- Create PCS designs to meet error budget requirements
- Develop operational concepts from coarse to fine pointing modes
- Selected hardware based on current technology and flight heritage
- Chosen two baseline architectures for analysis
  - Passive isolation system
  - Active isolation system

Two Approaches to Vibration Isolation

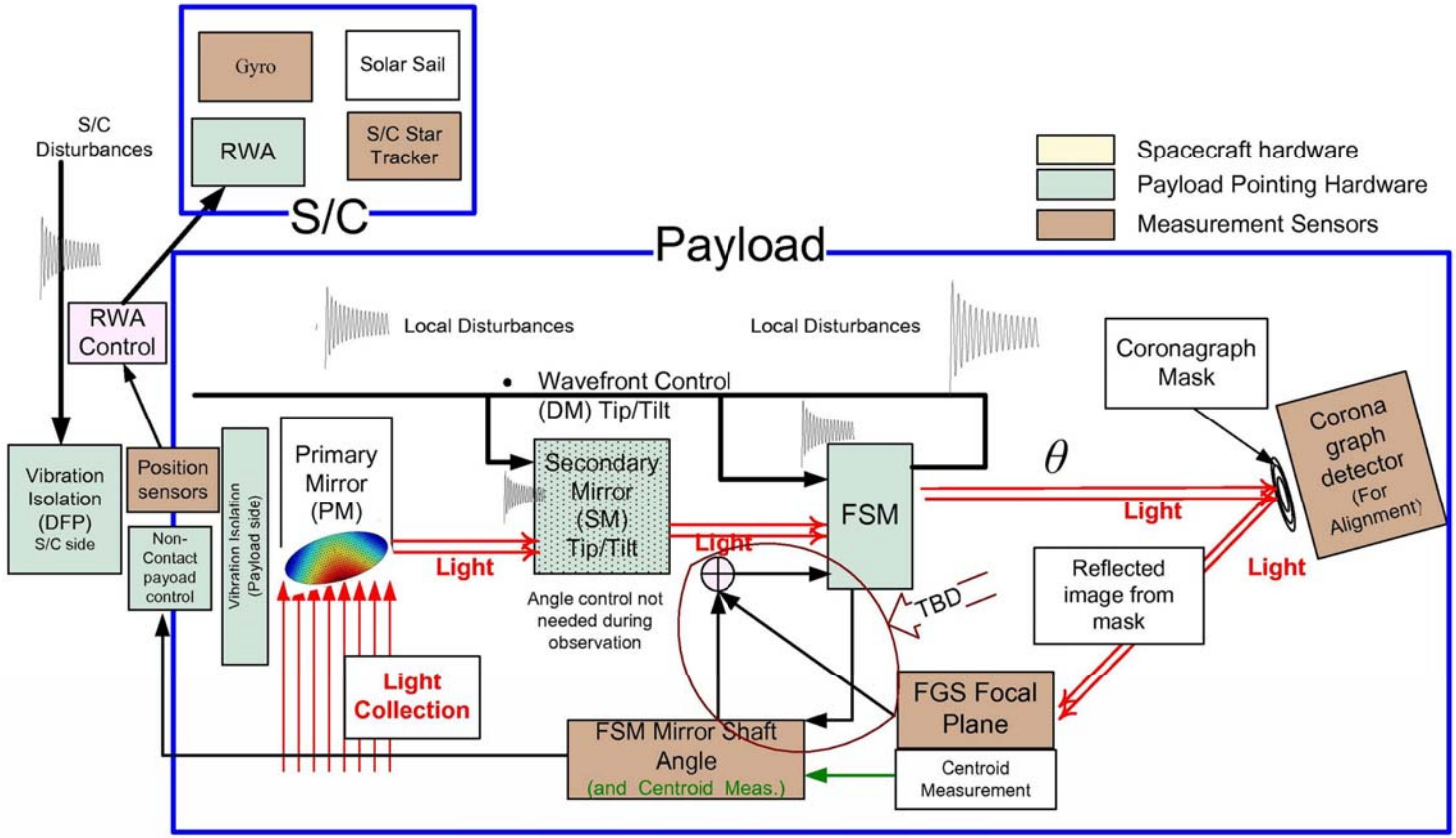
- Two-stage passive isolation design
  - First stage on reaction wheel assembly
    - Isolator struts modeled on Honeywell D-strut
    - 1.5Hz target frequency
  - Second stage at bus-payload interface
    - 1Hz target frequency
  - Selected modal damping
- Active isolation design
  - Disturbance free payload (DFP) architecture (Lockheed Martin)
  - Instrument payload and spacecraft bus connected only by cables
  - Payload/spacecraft non-contact actuators and payload attitude sensors provide precision inertial pointing of payload by reacting against mass of spacecraft
    - 0.5 Hz target payload pointing bandwidth
  - Spacecraft attitude control driven to maintain non-contact actuator finite stroke/gap
    - 0.015 Hz target relative attitude control bandwidth

Passive Architecture



- Use of passive isolation requires RWA, SM, and FSM control for maintaining pointing control. Note that the reaction wheels must point the entire S/C

Active Architecture



- Current Analysis shows that both SM and FSM control not needed during observation, but only the output from the FGS focal plane. The green arrow replaces the circled area.
  - The current architecture is still showing the FSM loop until the noise models have been more developed.
  - Both the FSM and SM control are required for the case of passive isolation
- Note that the active isolation position sensors are used to drive reaction wheel control

PCS Requirement – Contrast and Optic Performance

- Top level contrast requirements

Beam Walk	LOS	LOS mask error	Structure Deformation	SD mask error	PM deformation	PM def. mask error	**Total contrast**
1.90E-12	9.04E-14	5.46E-13	2.75E-17	1.64E-17	8.55E-13	5.19E-15	**3.40E-12**

- Opto-mechanical responses:
  - Image position (line-of-sight (LOS) errors)
    - Image jitter (σ) <= 0.3 mas (1σ)
    - Image offset (Ω) <= 0.3 mas
  - Beamwalk on each optic identified in error budget
    - Beamwalk due to pointing (after all control loops closed) <= 0.04 mas
  - Zernike amplitudes (aberrations): structure deformation and deformation of optic

$$C_{pointing} = c_1\sigma^4\Omega^4 + c_2\sigma^6\Omega^2 + c_3\sigma^2\Omega^6 + c_4\sigma^8 + c_5\Omega^8$$

Zernike mode	SD Aberr (nm)	PM Aberr. (nm)
4	4.78E-02	4.00E-01
5	6.21E-03	4.00E-01
6	4.58E-02	4.00E-01
7	2.50E-03	2.00E-01
8	6.00E-03	4.00E-01
9	3.48E-03	3.00E-01
10	4.41E-03	4.00E-01
11	1.29E-04	5.00E-03
12	1.44E-04	5.00E-03
13	3.77E-05	5.00E-03
14	7.95E-05	5.00E-03
15	4.56E-05	5.00E-03

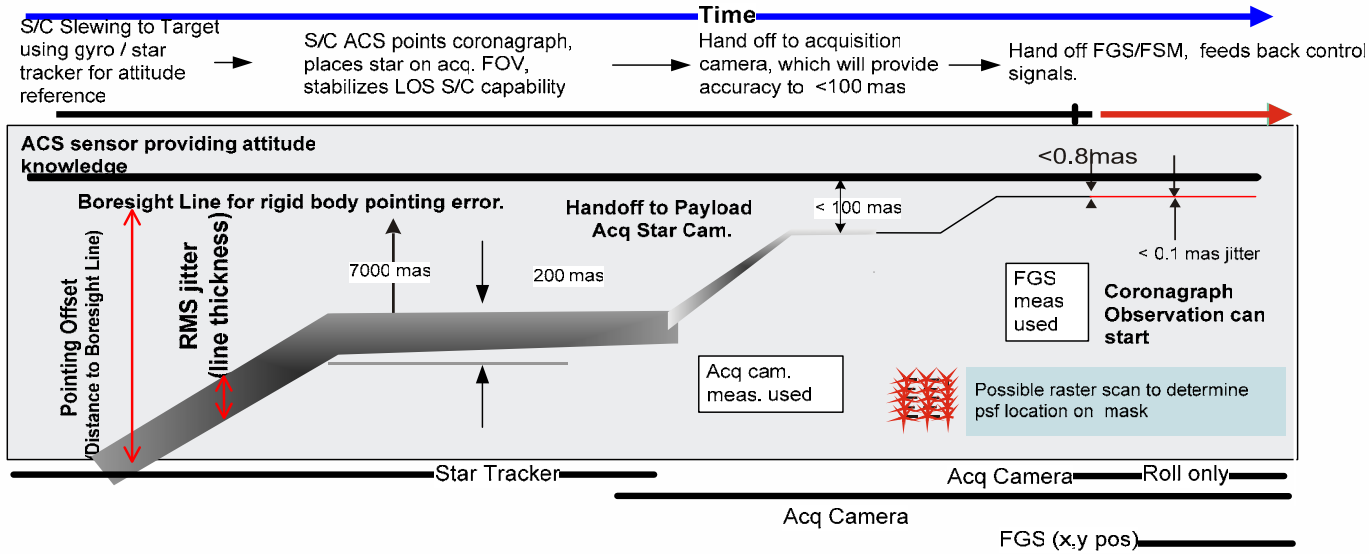
PCS Requirement – Physical motions

- Physical motions
  - Rotation and translation requirements on first 3 optics following PM and coronagraph box

	Rx (nrad)	Ry (nrad)	Rz (nrad)	Tx (nm)	Ty (nm)	Tz (nm)
SM	1.829	1.216	5.226	2.643	5.518	1.076
Fold 1 (M3)	10.050	10.050	10.050	100.500	100.500	100.500
Fold 2 (M4)	10.050	10.050	10.050	100.500	100.500	100.500
Coronagraph Box	10.050	10.050	10.050	10.050	10.050	10.050

  - Rigid body pointing
    - X/Y axis (tip/tilt) jitter < 4 mas (1σ)
    - Z axis (around LOS) ~ 1asec (1σ)
- Operational efficiency requirement: slew/settle time for a 30 degree dither must be completed in 30 minutes

Acquisition Layout

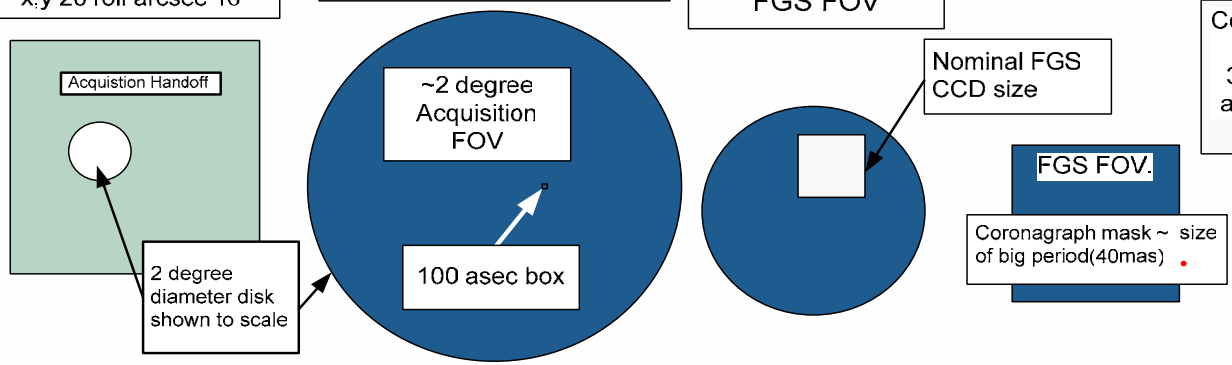


S/C Star Tracker
8 -15 deg FOV
8x8 degree shown
Typical Accuracy (7 asec x,y 20 roll arcsec 1σ

~2 deg Acquisition FOV
1000x1000 CCD gives
~100 mas accuracy/axis 1σ

10 arc second stop, nominal FGS FOV

Coronagraph FOV
3 asec x 3 asec (TBD)

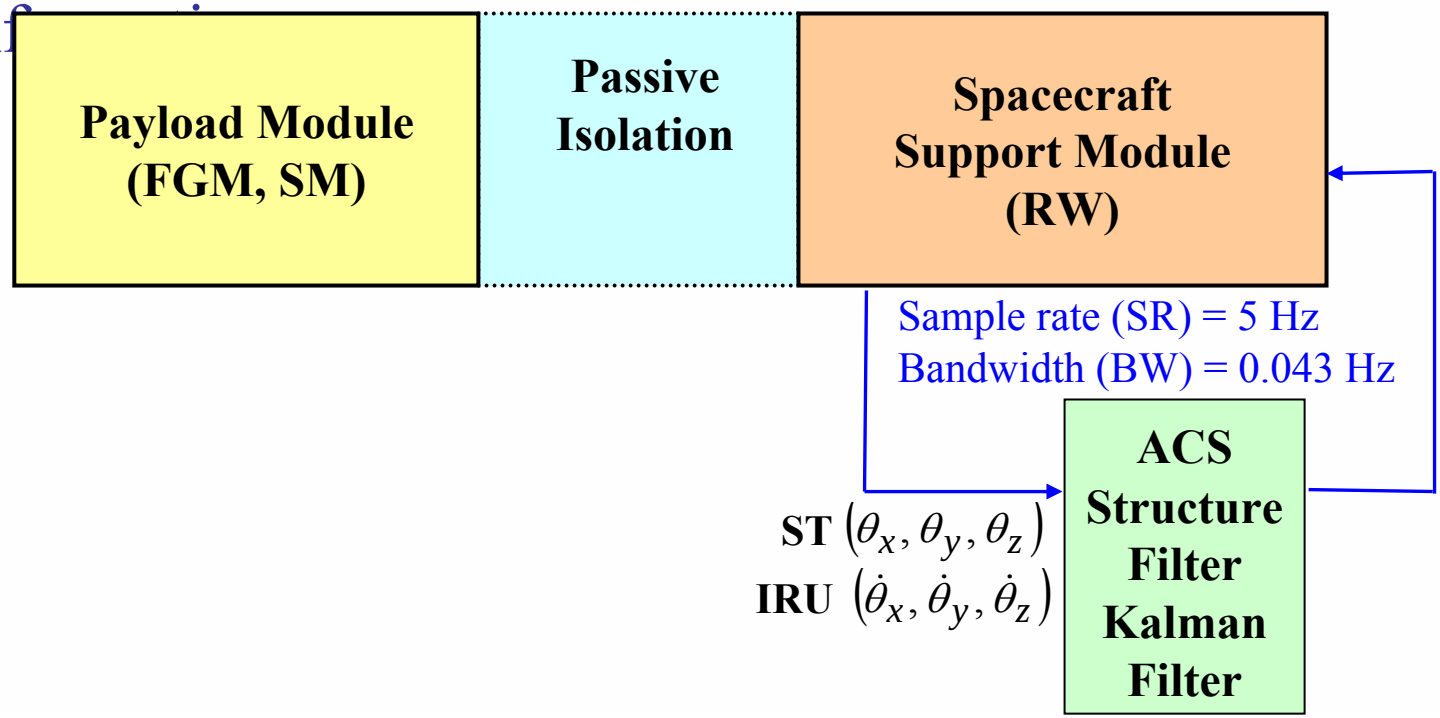


Operational Modes

- Coarse Mode
  - Rigid body slewing and coarse pointing
  - Requirement:
    - Accuracy 7 asec
    - Coarse pointing stability <1 asec (1σ)
  - Primary stability in coarse mode from the gyros.
- Acquisition Mode
  - Guide star image to fine guidance sensor (FGS) field of view (FOV)
  - Requirement:
    - Accuracy better than 1 asec
    - Stability from Payload Star Acquisition Camera (PSAC) <100 mas (1σ)
    - Accuracy limited by alignment stability to coronagraph
- Fine Pointing Mode
  - Stabilize image position on mask using fine guidance mirror (FGM) or fine steering mirror (FSM)
  - Requirements: contrast, optical performances, and physical motions (see error budget)

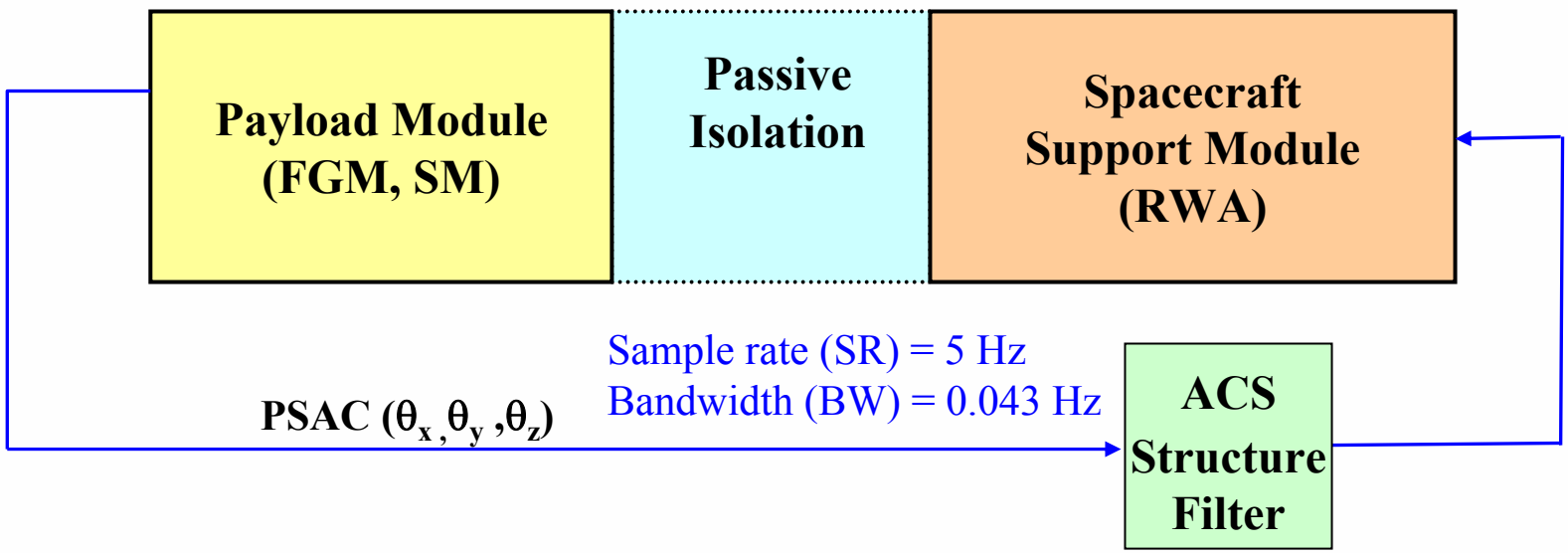
Coarse Mode – Passive System

- 3-axis inertially stabilized attitude control system (ACS)
- Actuators: 6 reaction wheels (RW) to point observatory (payload + spacecraft support module)
- Sensors/estimators: Kalman filter on gyros (IRU) and star trackers (ST) signals to provide 3-axis attitude inf



Acquisition Mode – Passive System

- Similar to coarse mode with tighter pointing and sensing requirements
- Actuators: 6 reaction wheels
- Sensors: payload star acquisition cameras (PSACs) provide 3-axis attitude information and rate derivation

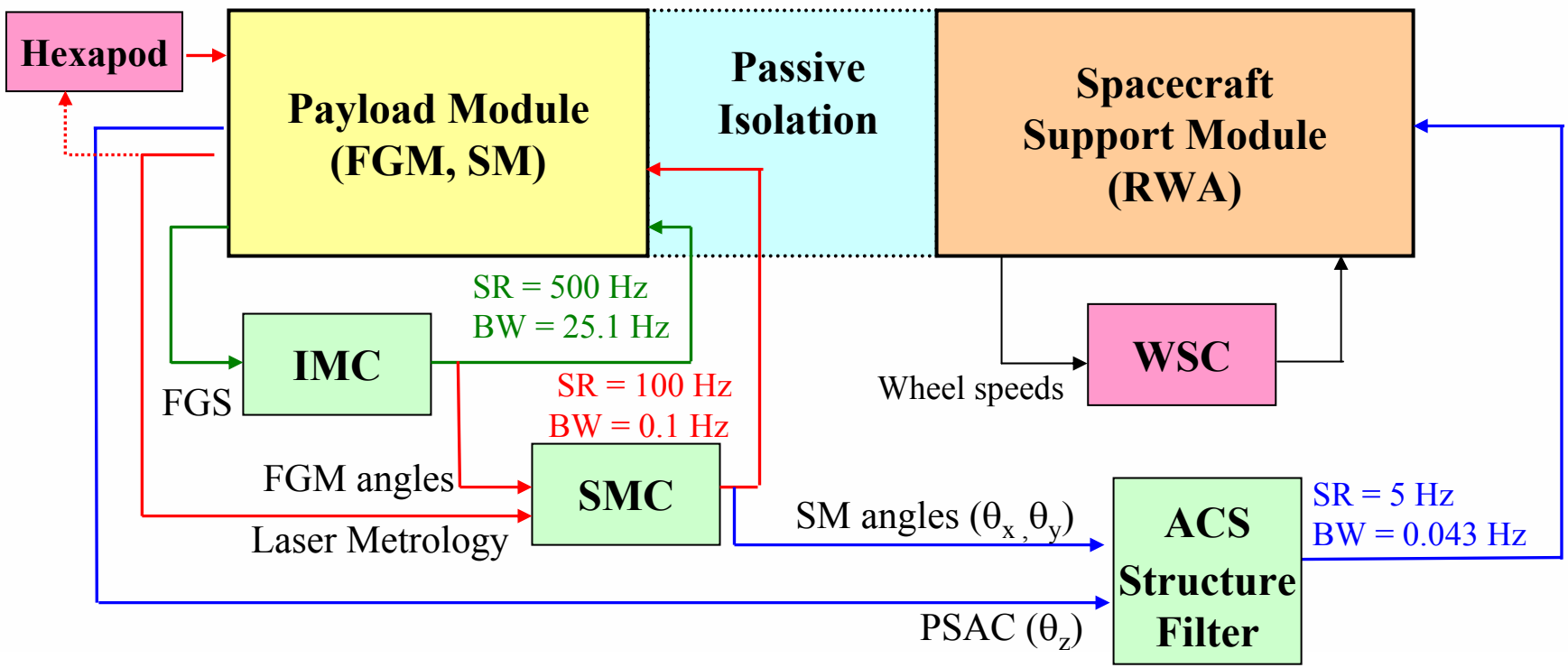


Fine Pointing Mode – Passive System

- Rigid body fine pointing (ACS)
  - Reduce low frequency and constant external disturbances
  - Actuator: 6 reaction wheels
  - Sensor: PSAC used only for roll information (θ_z) around LOS, and SM motions (feedback from position) used for θ_x and θ_y information
- Secondary mirror control (SMC)
  - Compensate for thermal drift between Payload Modules and Spacecraft Support Module
  - Provide additional tip/tilt pointing correction
  - Actuators: 6-axis hexapod actuator
  - Sensor: laser metrology, tip/tilt angles of FGM
- Image motion control (IMC)
  - Attenuates high frequency θ_x and θ_y errors
  - Actuators: fine guidance mirror (FGM)
  - Sensor: fine guidance sensor (FGS)

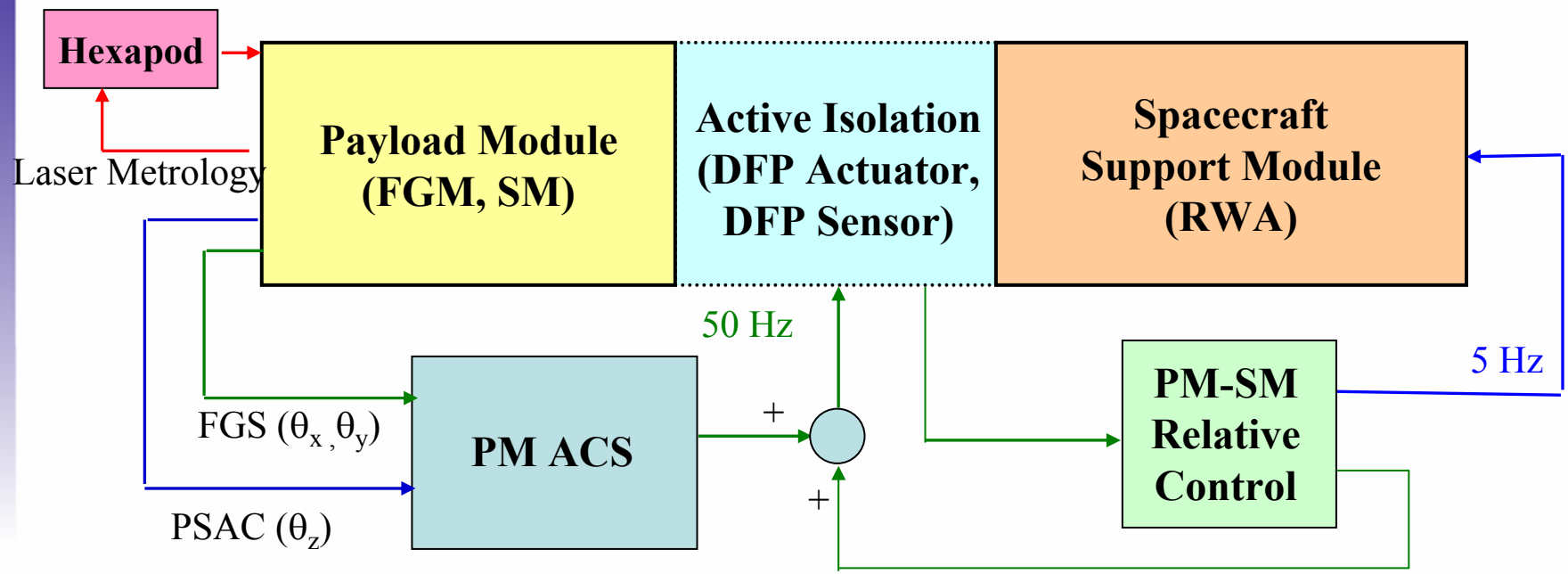
Fine Pointing Mode – Passive System

- Features three "staged" control systems
  - Rigid body control off-loads secondary mirror control
  - Secondary mirror control off-loads fine guidance mirror control
- Other control loops
  - Wheel speed control (WSC) compensates for wheel drag torque
  - SM hexapod control uses laser metrology feedback signals to stabilize low frequency (thermal drift) motions between SM and PM

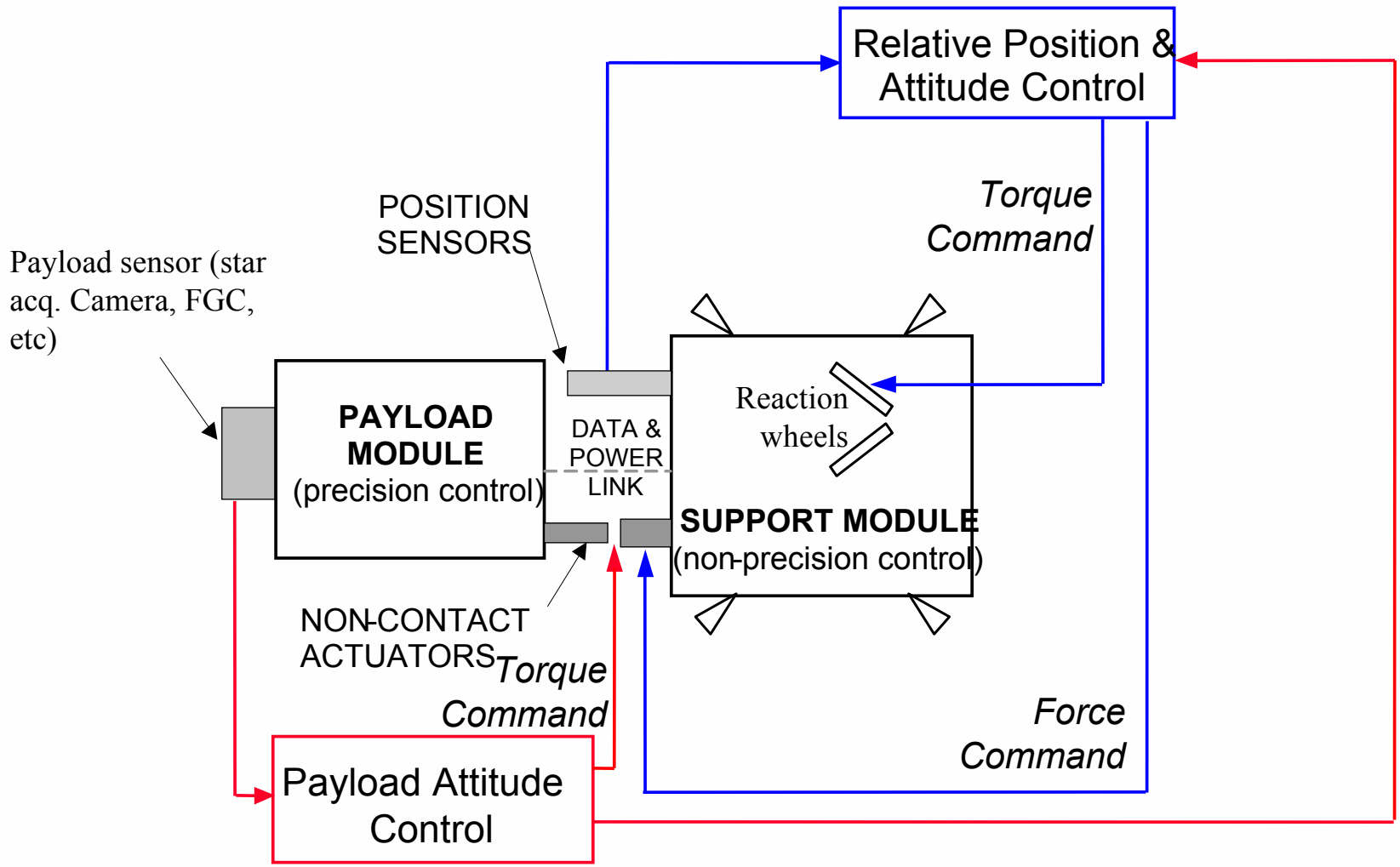


Fine Pointing – Active System

- 3-axis inertially-stabilized control system for Payload Module, using Payload Module FGS and PSAC and DFP non-contact actuators
- FGM line-of-sight control not necessary
- Sec. translation control to maintain Prim-Sec. trans. align.
- S/C Support Module inertial attitude control and Payload Module-S/C Support Module relative translation control using IF sensors to maintain interface stroke/gap



Pointing Modes (Acquisition, Coarse, Fine) – Active system



Representative Actuator Descriptions - Spacecraft

- Reaction wheel assembly
  - Collected wheel information from Goodrich, Honeywell, and Teldix
  - Baseline six Goodrich wheels
- Wheel performance specs
  - Torque limit = 0.3 Nm
  - Momentum limit = 50 Nms
- Wheel Disturbances
  - Harmonic disturbances – included 8 harmonics from Goodrich data
  - Torque quantization (16-bit D/A)
  - Torque noise ~6.4e-4 N-m/Hz$^{1/2}$ (0.1-1 Hz)
  - Nonlinear drag torque and torque ripple effects

Goodrich E-wheel

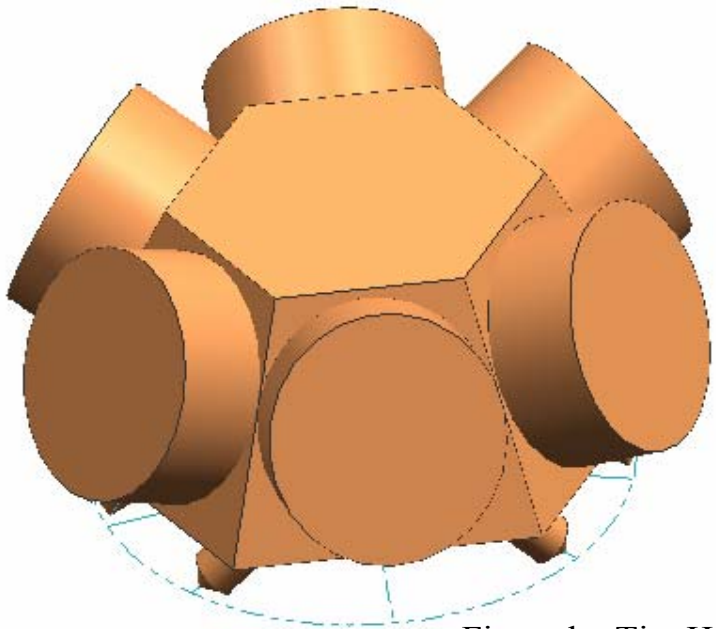


Figure by Tim Ho

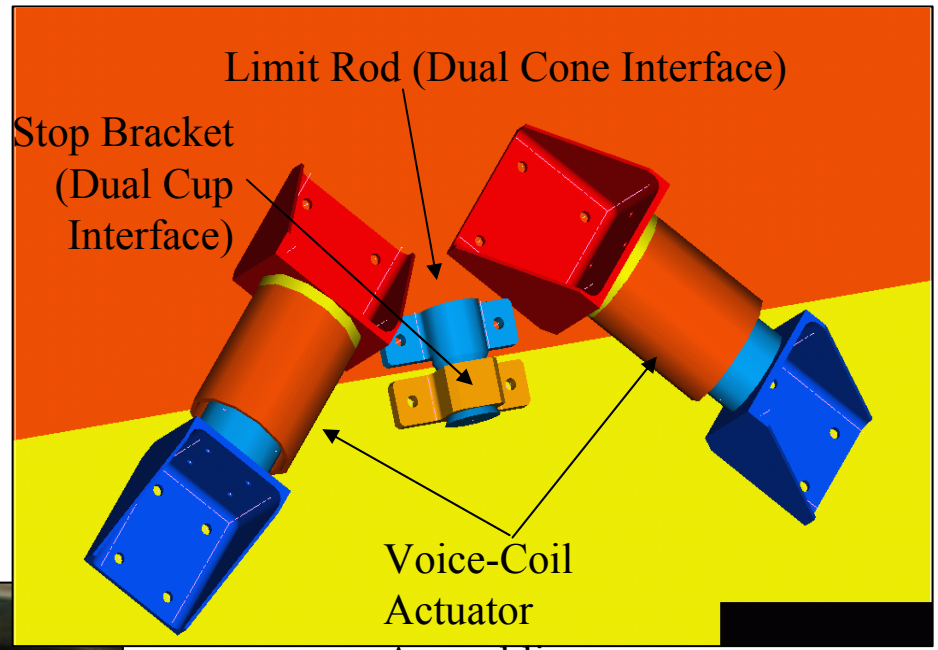
Representative Actuator Descriptions - Payload

- Secondary Mirror (SM)
  - Six axis hexapod
  - Piezoelectric actuators
  - 100Hz first mode
  - Correct for relative position and rotation between primary and secondary mirror
  - Stroke ≈ 200 nm
- Fast steering mirror (FSM)
  - Two-axes tip/tilt mirror
  - Small range of motion
  - Consider re-actuated design to reduce disturbances
  - Uses fine guidance camera for feedback signals
  - Stroke ≈ 100 asec

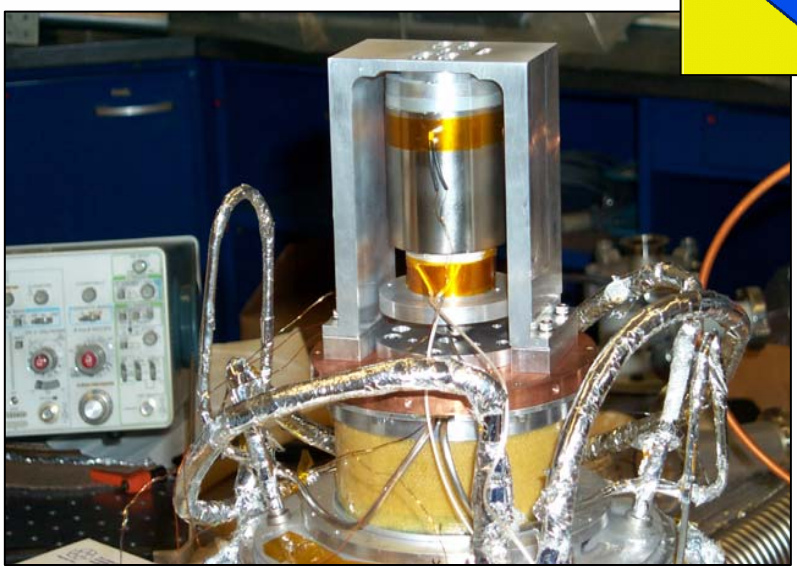
PI six-axis hexapod

Active System Actuator – DFP

DFP single actuator assembly



DFP typical mechanical design



DFP actuator cryogenic testing

Representative Sensor Descriptions - Spacecraft

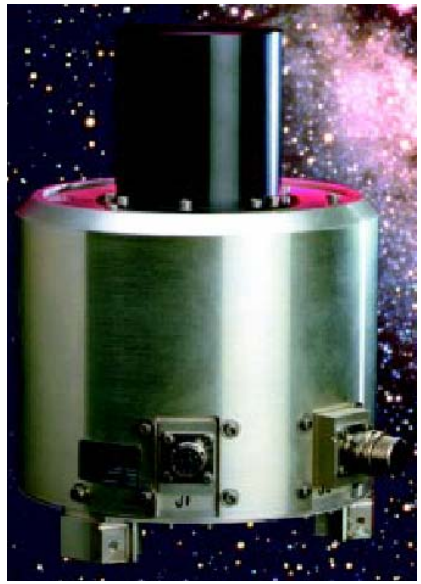
- Star tracker
  - 8-15 deg FOV
  - (5, 5, 20) arcsec 1σ
  - Update rate ~10 Hz
- Gyros
  - 2-3 axis IRU
  - SKIRU D-II

    σ_u= 1.33e-5 arcsec/sec$^{1.5}$

    σ_v= 0.019 arcsec/sec$^{0.5}$

    Max rate = 2 deg/sec
  - Update rate > 2 Hz
- Wheel tachometer
  - Digital pulse outputs (less noisy than analog outputs)
  - Performance depends on pulse resolution of the wheel (72 pulses/rev for E-wheel)

Ball CT-602

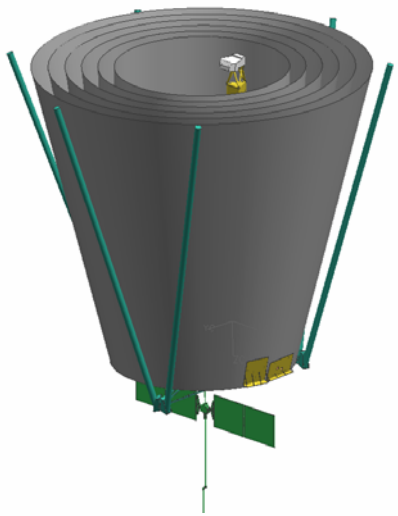


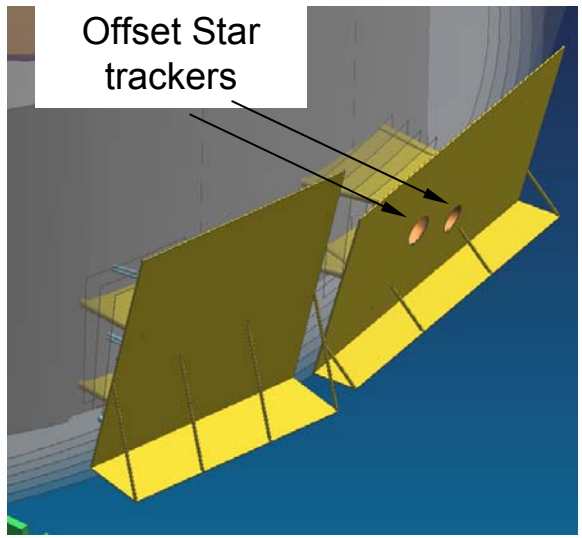
SKIRU D-II

- Redundant - Three-Axis IRU
- No-Single-Point of Failure
- NASA Standard

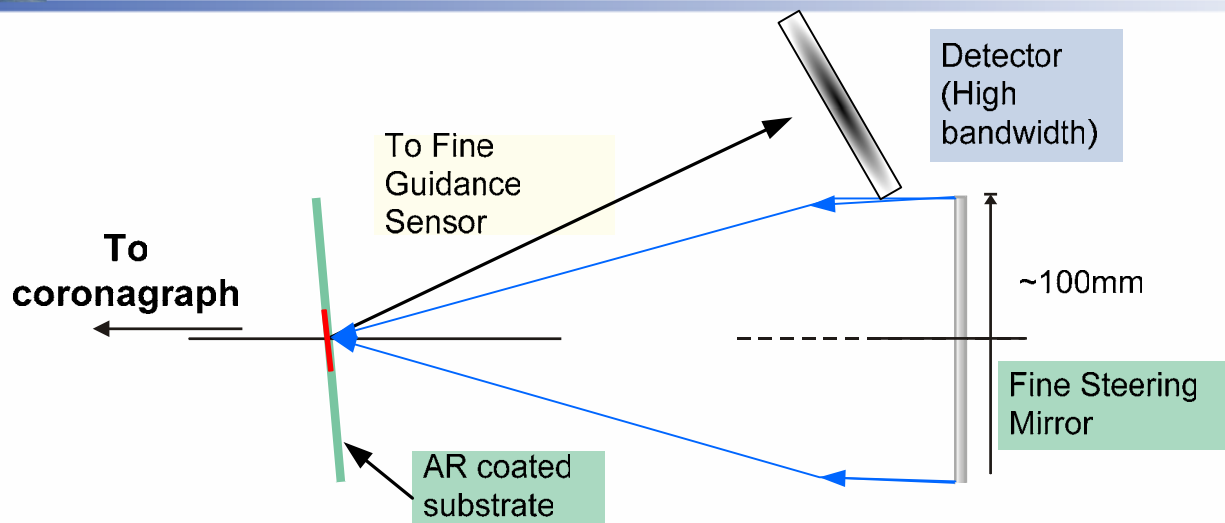
Payload Star Acquisition Camera Concept

- Payload Star Acquisition Camera System
  - Pair of star trackers (sep angle > 30deg) -- Based on SIRTF/AXAF high precision type star cameras
    - Narrow FOV (2 -5 degrees), collecting optics ~10cm, multiple star tracking;
    - Provide full sky coverage, current design shows looking through baffle
    - Sample at 5 Hz
  - Will bridge gap between star tracker accuracy and coronagraph occulting spot
  - Could also be used for guiding for ancillary science at less precision than the coronagraph mode. Expected relative accuracy better than 100mas
- Acquisition camera current placement (diagram Tim Ho). Cycle 2 will revisit placement.





Fine Guiding System Concept



Coronagraph plane mask & supporting substrate
Reflection from coronagraph mask backside or from AR coating on the substrate – at least 1% light returned. Assumes AR coating extends over to full field at the focal plane mask

FSM
Located near DM
Bandwidth ~ 8 to 40Hz
Stabilize image to ~ 0.03 mas
Resolution ~ 0.01 mas on sky

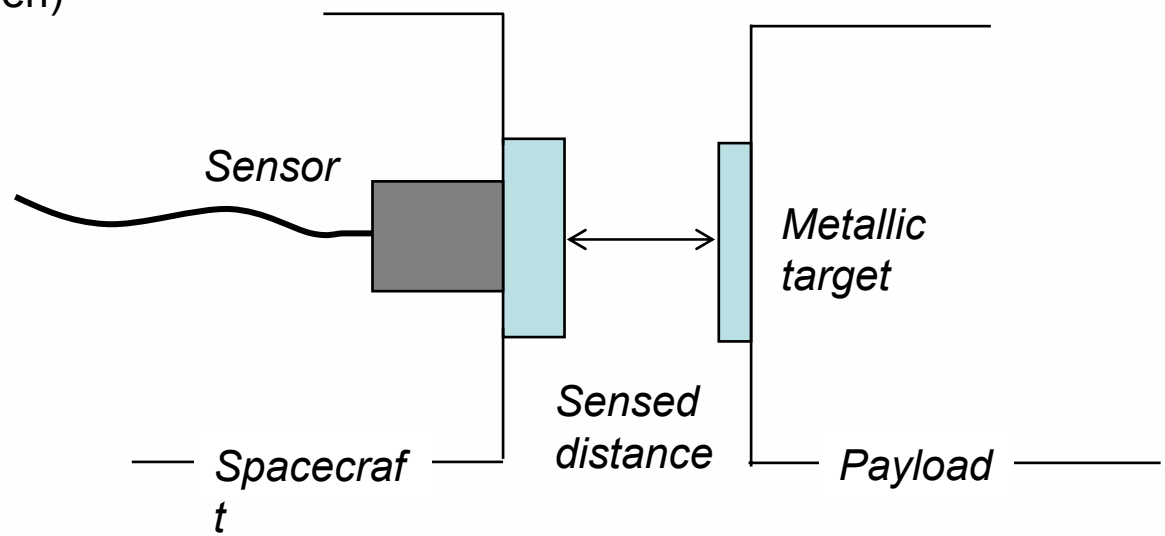
- Current concept
- Light reflected will return ~ 1% of light hitting.
- Detector pixels expected to subtend ~ 1mas to 10 mas

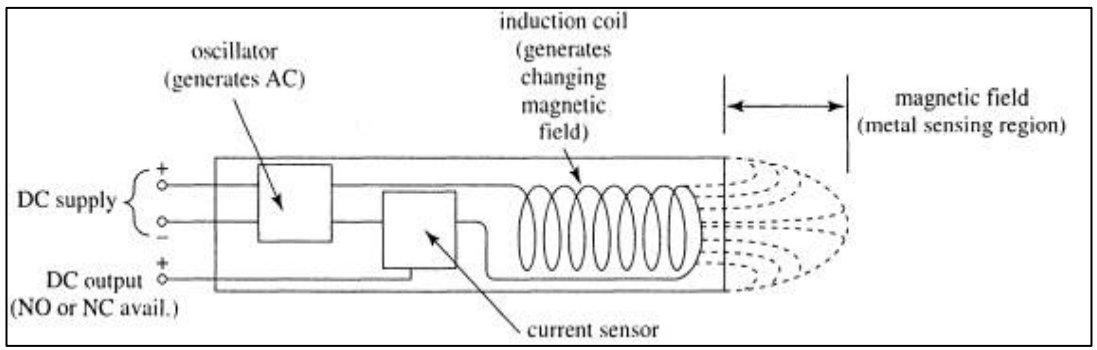
Fine Guidance Sensor

- Fine Guidance Camera System
  - Tracks from the star signal rejected from the coronagraph
    - Signal provided from coronagraph target stars ~7 mag.
      - *Mirror 8m x 3.5m --- large collection area*
      - *$\lambda_{0.6}/D_{8m}$ = 15.5mas. NEA requirement ~ 1/400 of $\lambda_{0.6}/D_{8m}$ in long axis*
      - *$\lambda_{0.6}/D_{3.5m}$ = 35.3mas gives PSF parameters*
  - Angular measurement requirement on FGS driven by NEA requirement
  - FOV ~3 asec (3 to 10)
  - Fine guidance system designed by GSFC
  - FSM used for both image stabilization and determining maximum contrast alignment
    - possibly not needed during observation with active isolation
  - System must meet tight stability requirements
    - (LOS image jitter 1σ = 0.3 mas, beamwalk pointing jitter 1σ = 40 microarcsec as shown in current error budget (sampled at 100 Hz to 500Hz, TBR)

Active System Sensor: DFP Interface Sensors

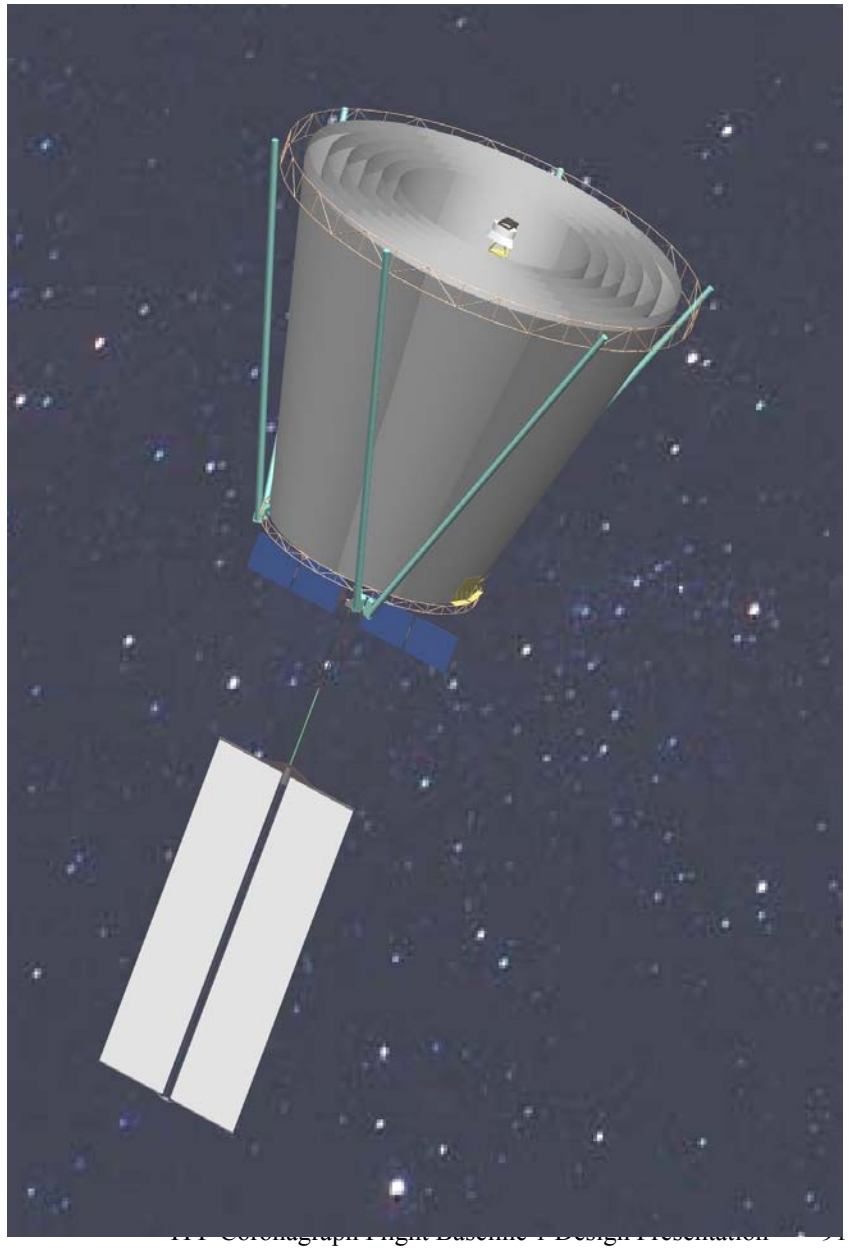
Sensors based on Inductive (Eddy-Current) Sensor Technology (mature, proven)





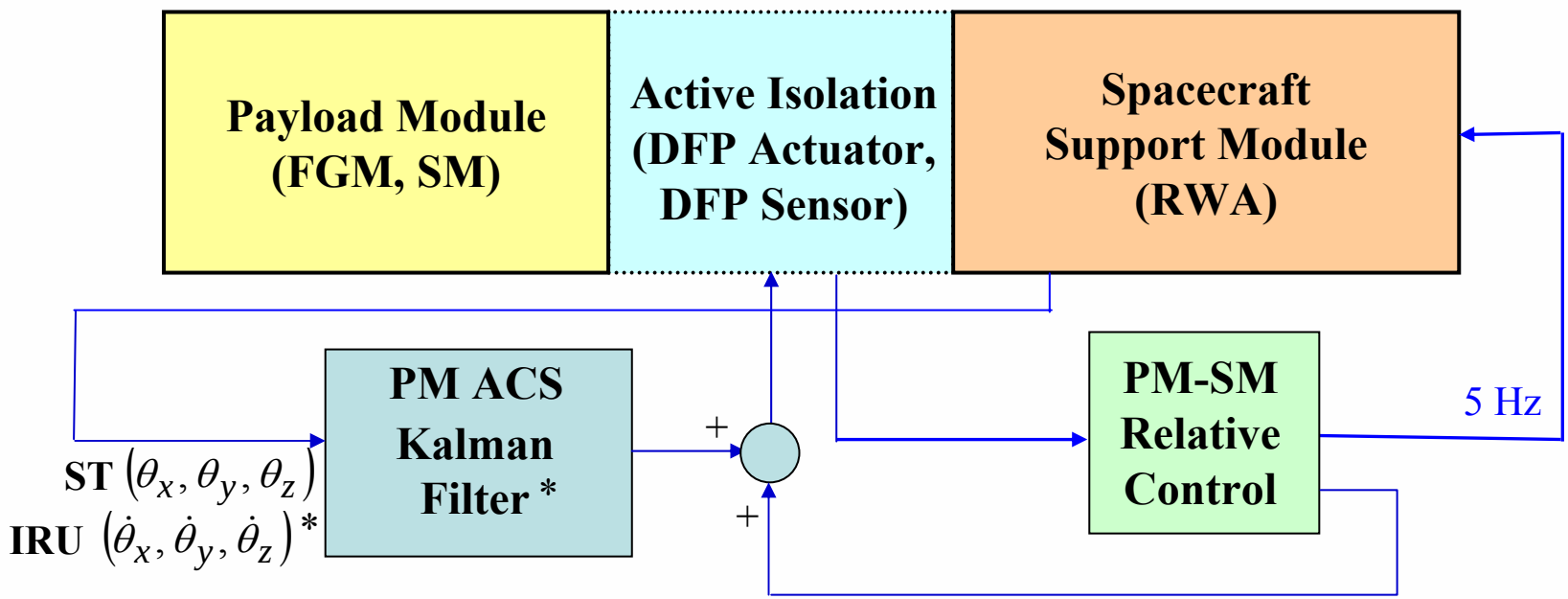
Candidate sensor: Kaman 26U	
Size	1 in. D., 1.5 in. L.
Range	±4 mm
Resolution	1-3 μm
Nonlinearity	8 μm

Backup Slides



Coarse Mode - Active System

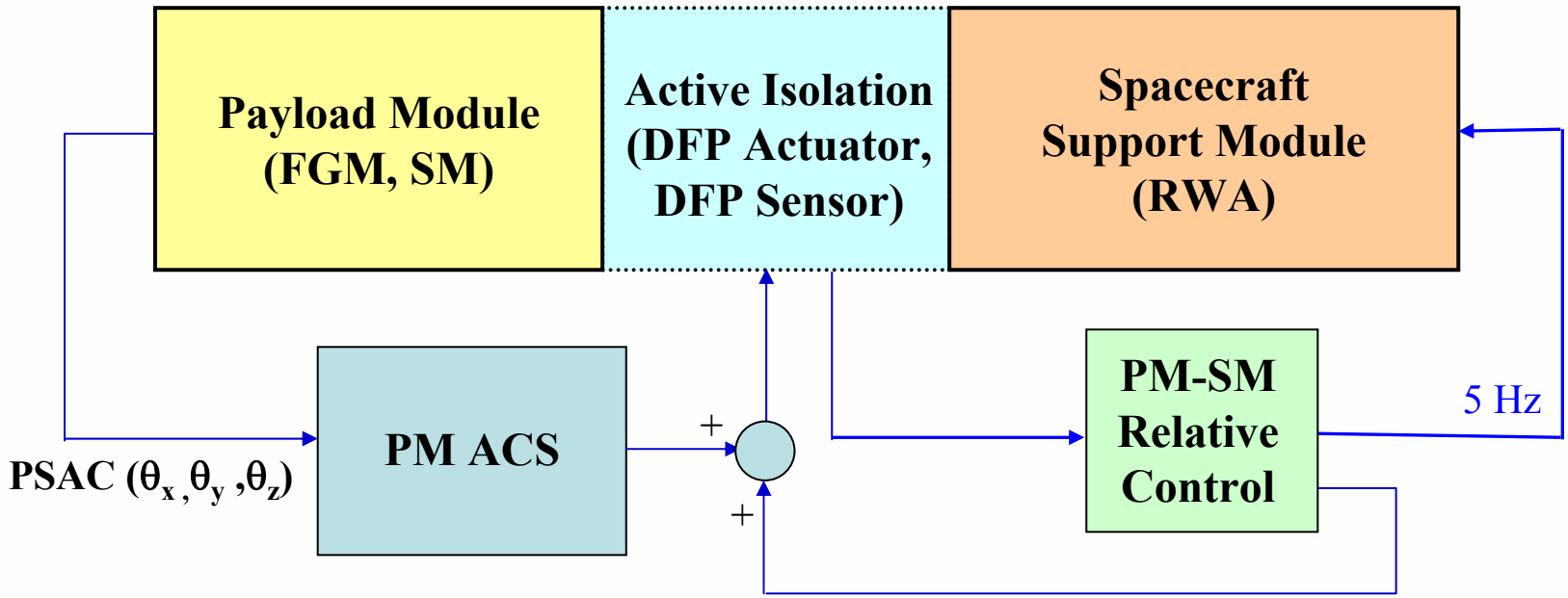
- 3-axis inertially-stabilized control system for S/C Support Module, using S/C Support Module star tracker and DFP non-contact actuators
- S/C Support Module inertial attitude control and Payload Module–S/C Support Module relative translation control using interface sensors to control interface stroke/gap



∗ PM Inertial rate sensor usage depends on sample rate of PM star trackers

Acquisition Mode – Active System

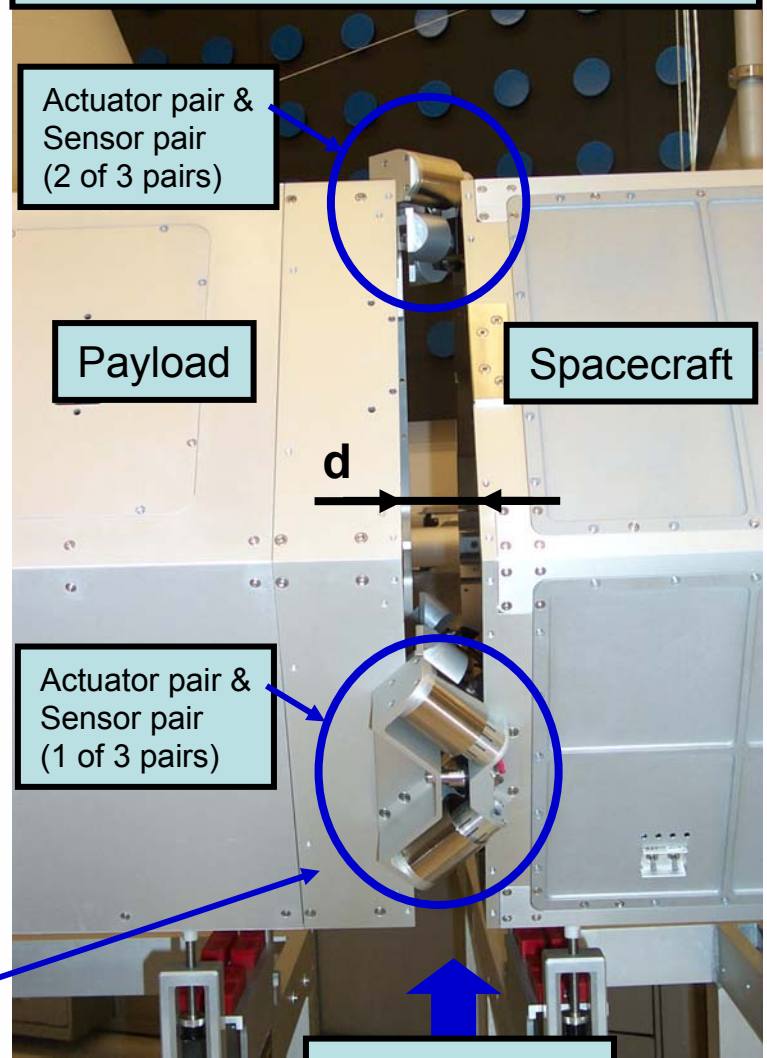
- 3-axis inertially-stabilized control system for Payload Module, using Payload star Acq camera and DFP non-contact actuators
- S/C Support Module inertial attitude control and Payload module-S/C relative translation control using interface non-contact sensors to maintain interface stroke/gap



DFP Payload-Spacecraft Interface

- DFP Interface volume
  - Three separate brackets requiring a volume of less than 2500 cm^3 each (21cm x 11cm x 10 cm)
- DFP Interface depth, d, can be as small as 5 mm
  - Shown in the picture with d = 60-mm
- Total DFP Interface mass
  - About 30 kg, including electronics boxes and launch locks

View of DFP Interface on DFP 3D Testbed



Full size sensors and actuators for large space system

Sensor Descriptions – DFP

- Current sensor selection: Inductive proximity sensor
  - Mature, proven technology
  - Models are available for cryogenic operation
  - Flight heritage
  - Candidate sensor: Kaman 26U
    - Sensor head dimensions: 1 in. Dia., 1.5 in. long
    - ±4 mm range
    - 0.8 µm resolution p-p (zero displacement – noise limited @ 10Hz bandwidth)
    - 3.8 µm resolution p-p (full scale displacement – noise limited @ 10Hz bandwidth)
    - Non-linearity: 8 µm (peak over full range)
- Alternative sensor technologies under evaluation
  - Capacitive sensors (flight heritage, and cryogenic operation)
  - Optical sensors

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NORTHROP GRUMMAN Space Technology
TC Technology
nightsky systems

TPF Terrestrial Planet Finder

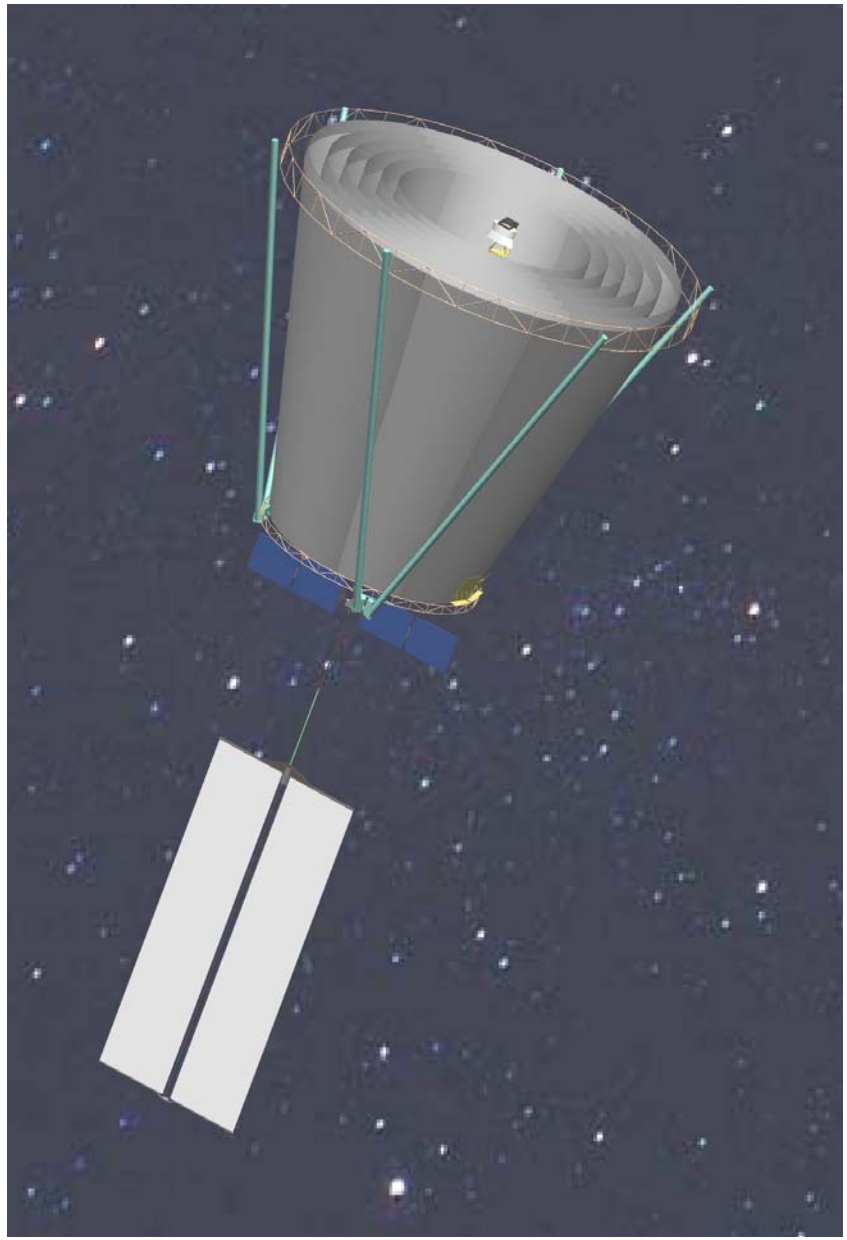
System Design and Configuration

Timothy Ho

Contributors:

T. Cafferty, C. Engler, V. Ford, P. Feher, A. Kissil, E. Kwack, P. Mouroulis, D. Lisman

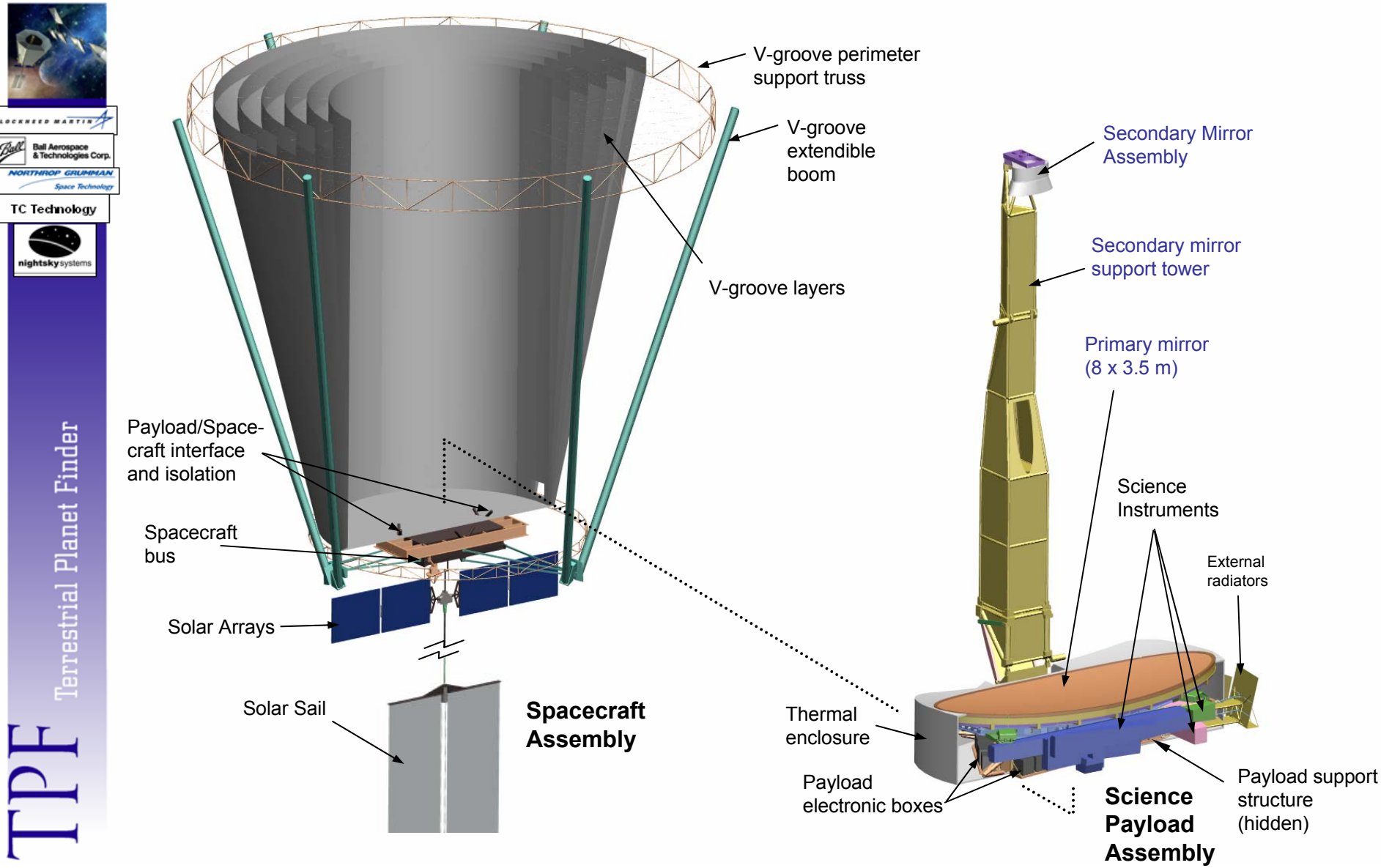
11-12 July 2005



Topics

- Deployed Configuration Overview / Science Payload
- Optical Telescope Assembly / Payload Support / Spacecraft Interfaces
- Optical Prescription Path
- Payload Support Assembly
  - Payload Support Structure
  - Instrument Locations
  - Payload Thermal Control
- Spacecraft Assembly
  - Bus / Reaction Wheels / Tanks
  - V-groove
  - Solar Array and Solar Sail
- Stowed Launch Configuration

Deployed Configuration Overview



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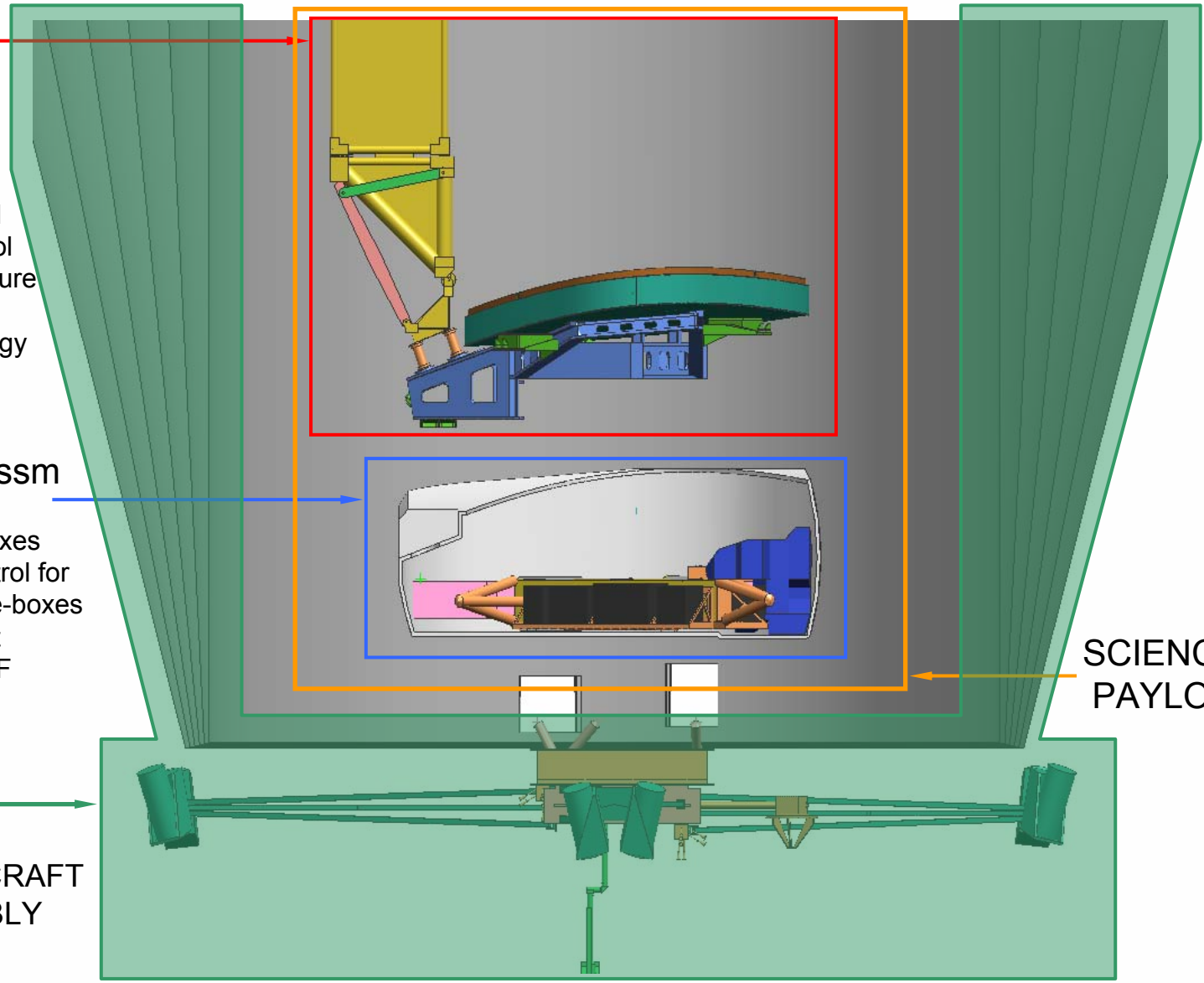
Science Payload Assembly

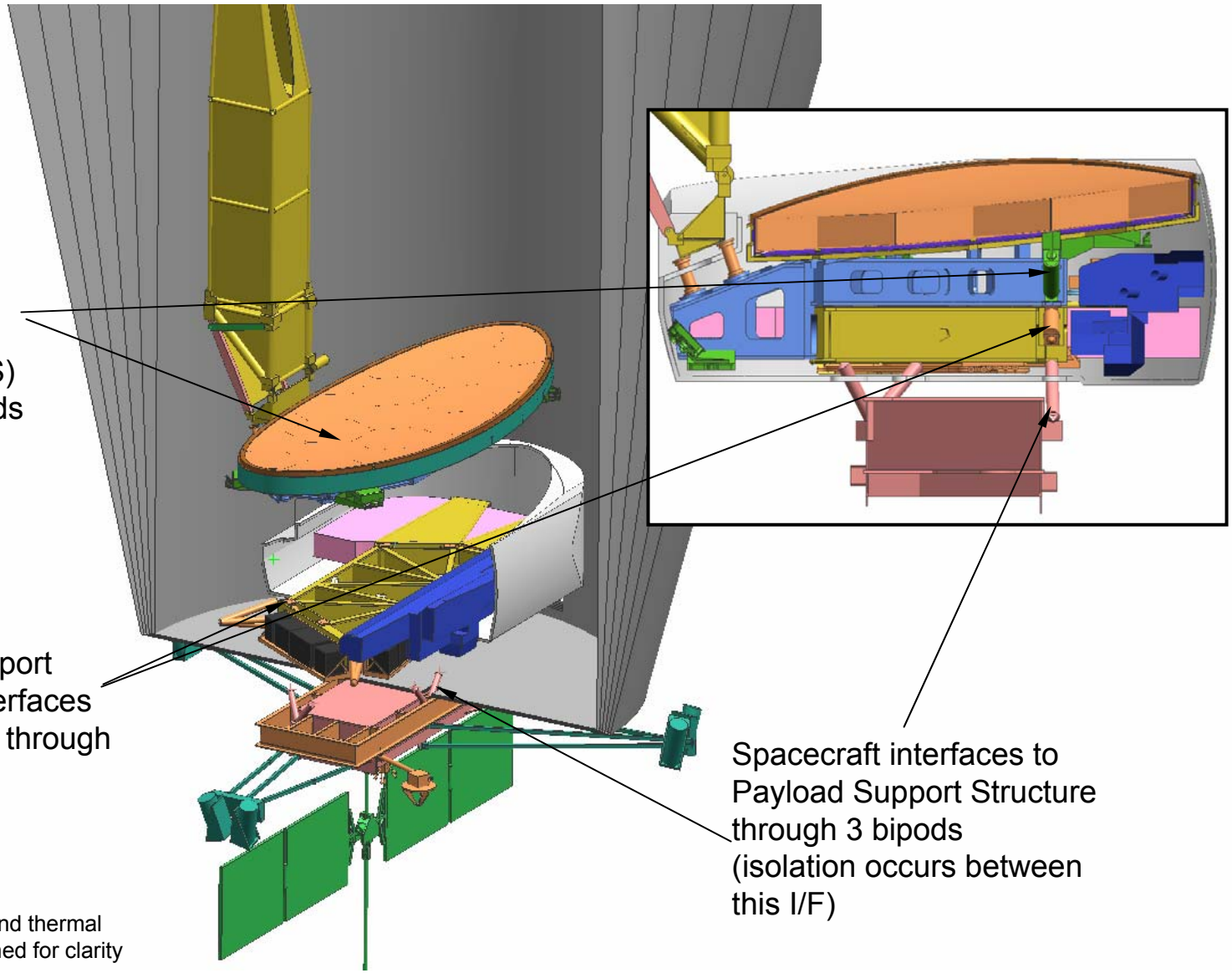
OTA
(Optical Telescope Assembly)
-Primary
-Secondary
-Tertiary
-Structural and thermal control support structure for mirrors
-Laser metrology

Payload Support Assm
-Instruments
-Electronic boxes
-Thermal control for detectors & e-boxes
-OTA Support
-Spacecraft I/F



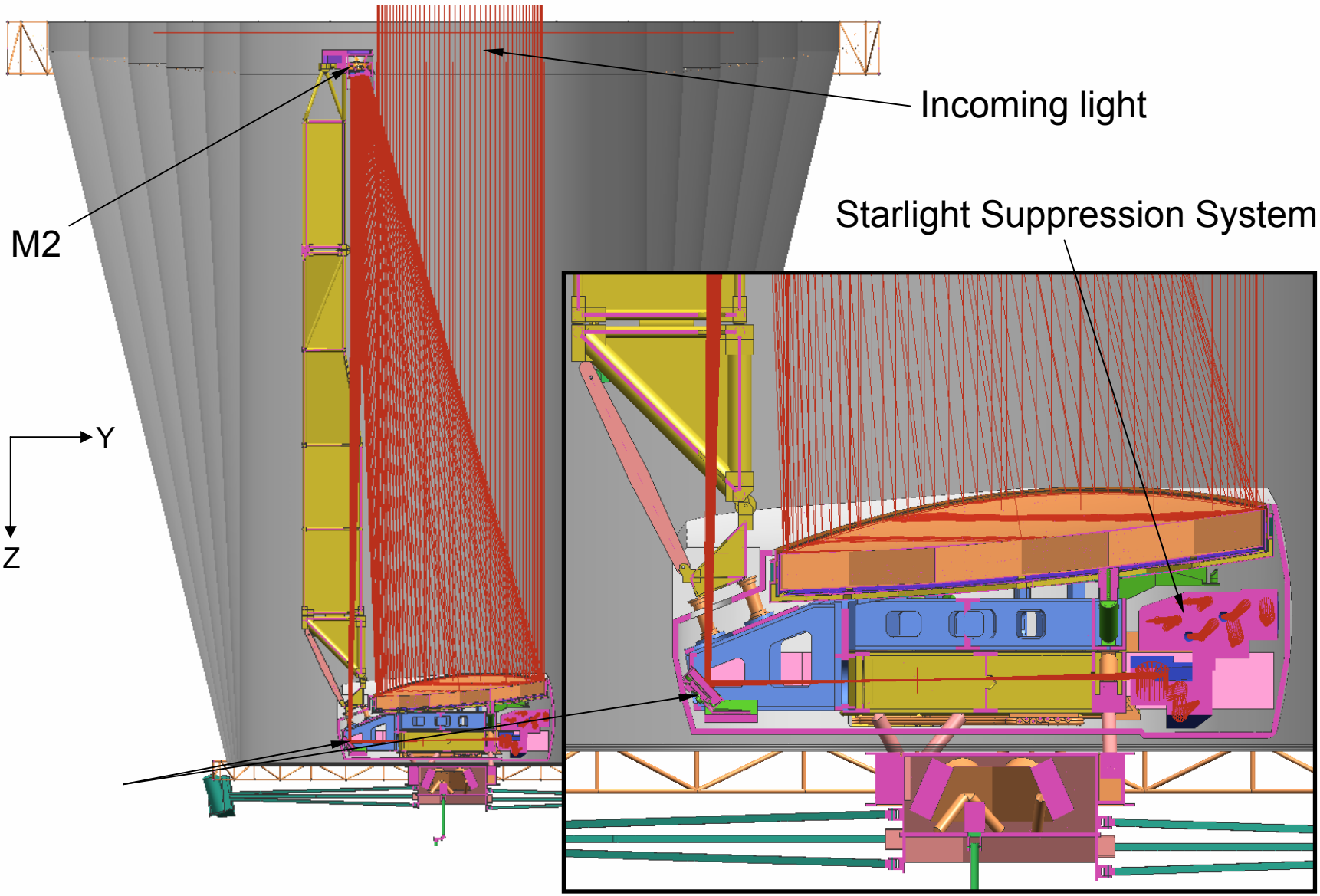
TPF Terrestrial Planet Finder

OTA / Payload Support / Spacecraft Interfaces



Note: V-groove and thermal enclosure sectioned for clarity

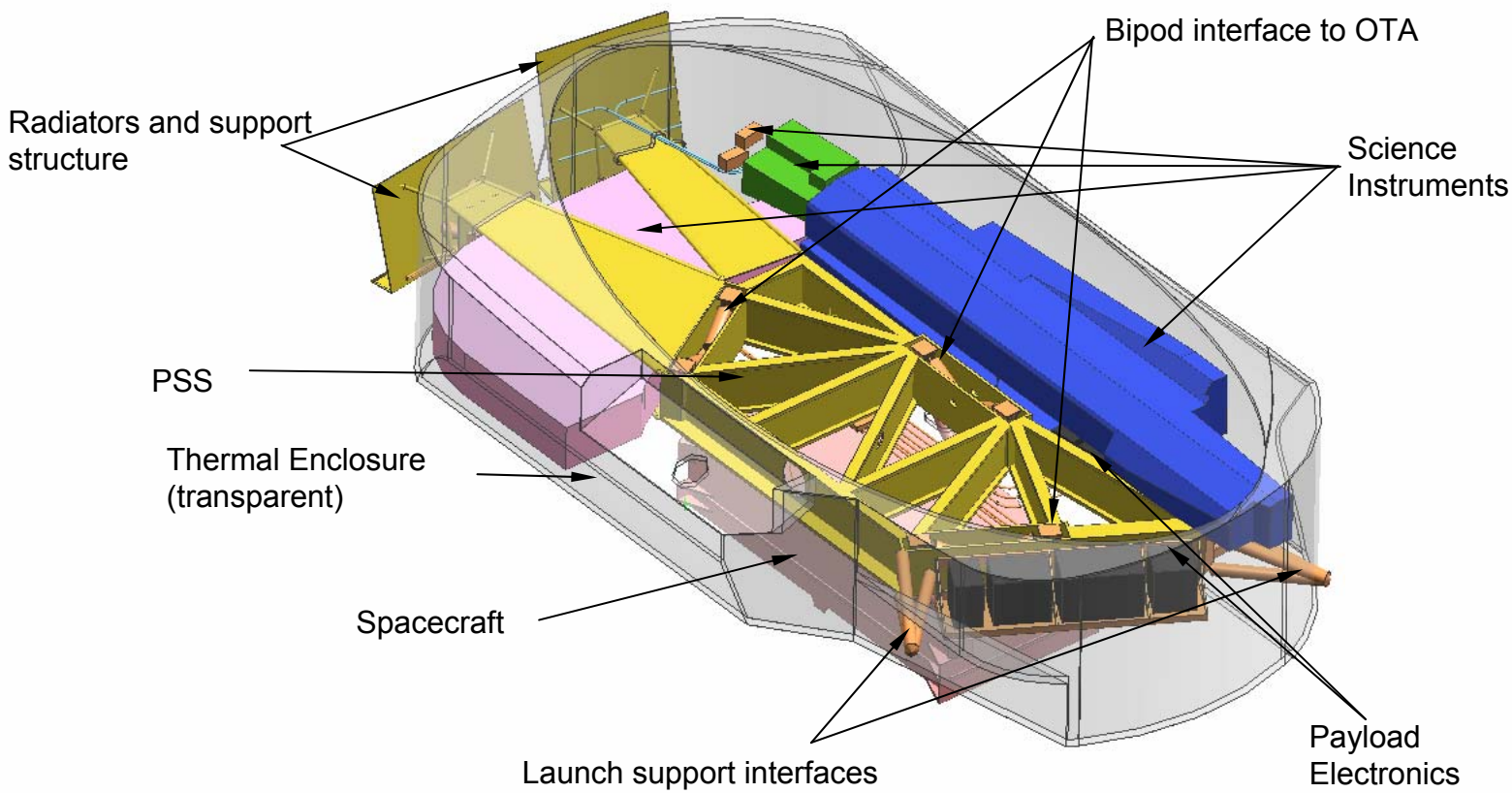
Optical Prescription Path



Payload Support Assembly

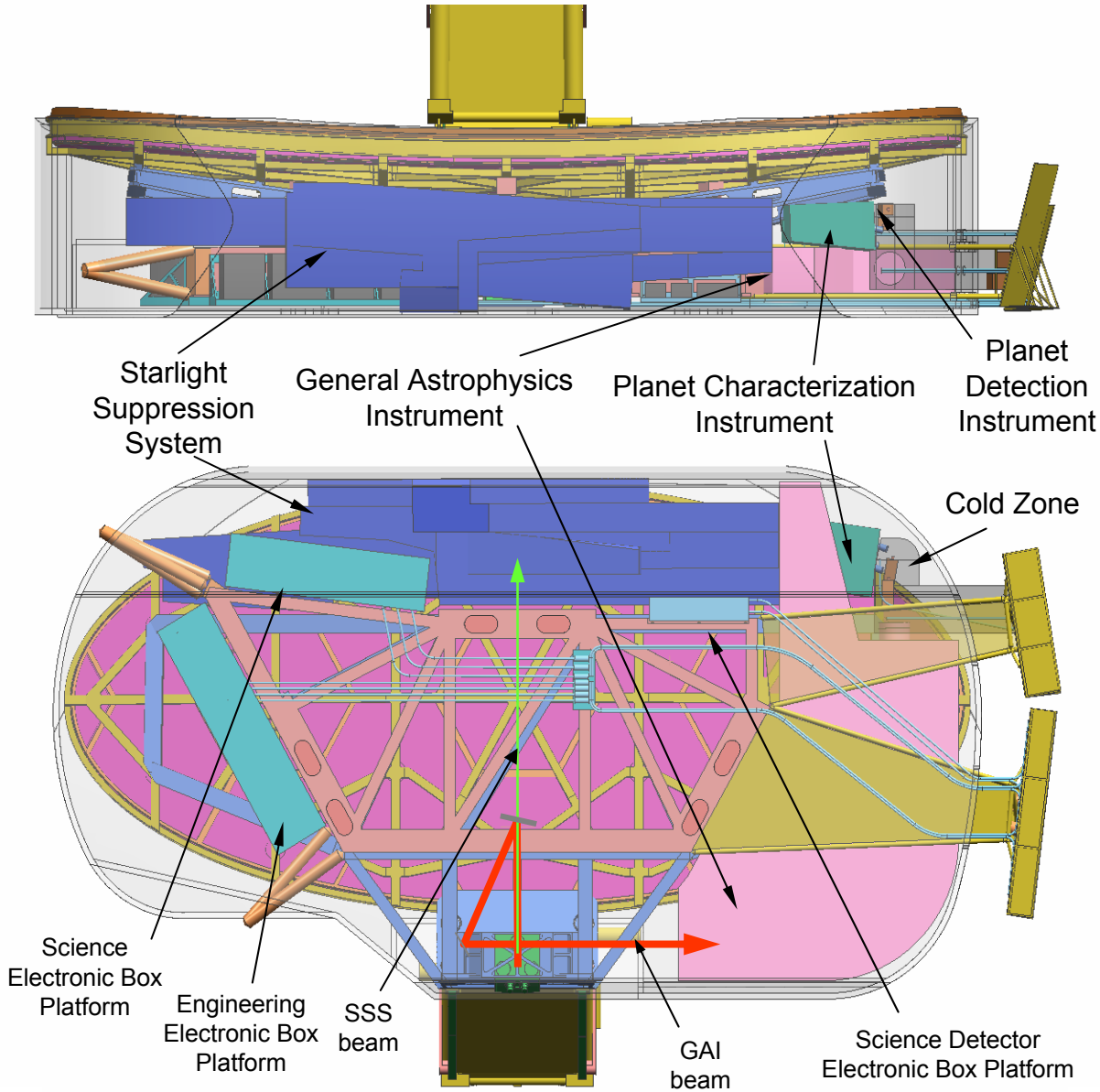
Payload Support Structure & Attachments

- The Payload Support Structure (PSS) is the main interface to the OTA and spacecraft
- Supports the science instruments, payload electronics, thermal control radiators/heat pipes and the thermal enclosure
- A main load carrying interface to the launch shroud PAF
- Provides a clean interface to OTA



Placeholder Science Instrument Locations

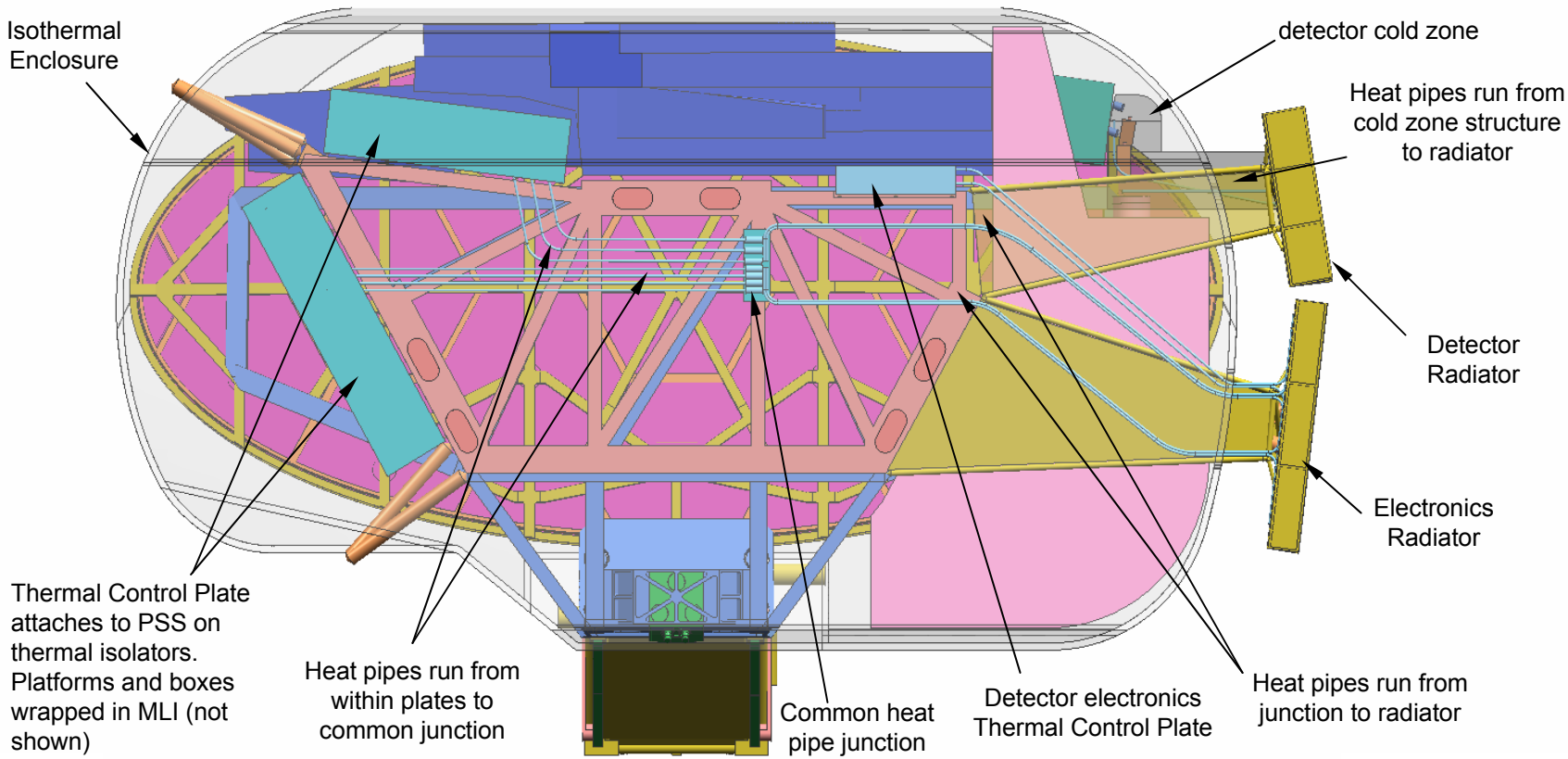
- Not preferred choices for instrument concepts
- Used to understand accommodation requirements
- From tertiary mirror of telescope, a pickoff mirror sends :
  - Outer portion (red arrow) of the beam to the GAI (assumed 10 arcsec – 4 arcmin)
    - Beam height limitation for GAI: 30 cm
  - Inner portion of the beam to the SSS (green arrow)
  - Light delivered to detection and characterization instruments through SSS



Payload Thermal Control

- Isothermal Enclosure surrounds warm portion of payload:
  - 290K – 305K
- Cold zone enclosing detectors isolated from warm zone:
  - assumed temperature: -100C±5C

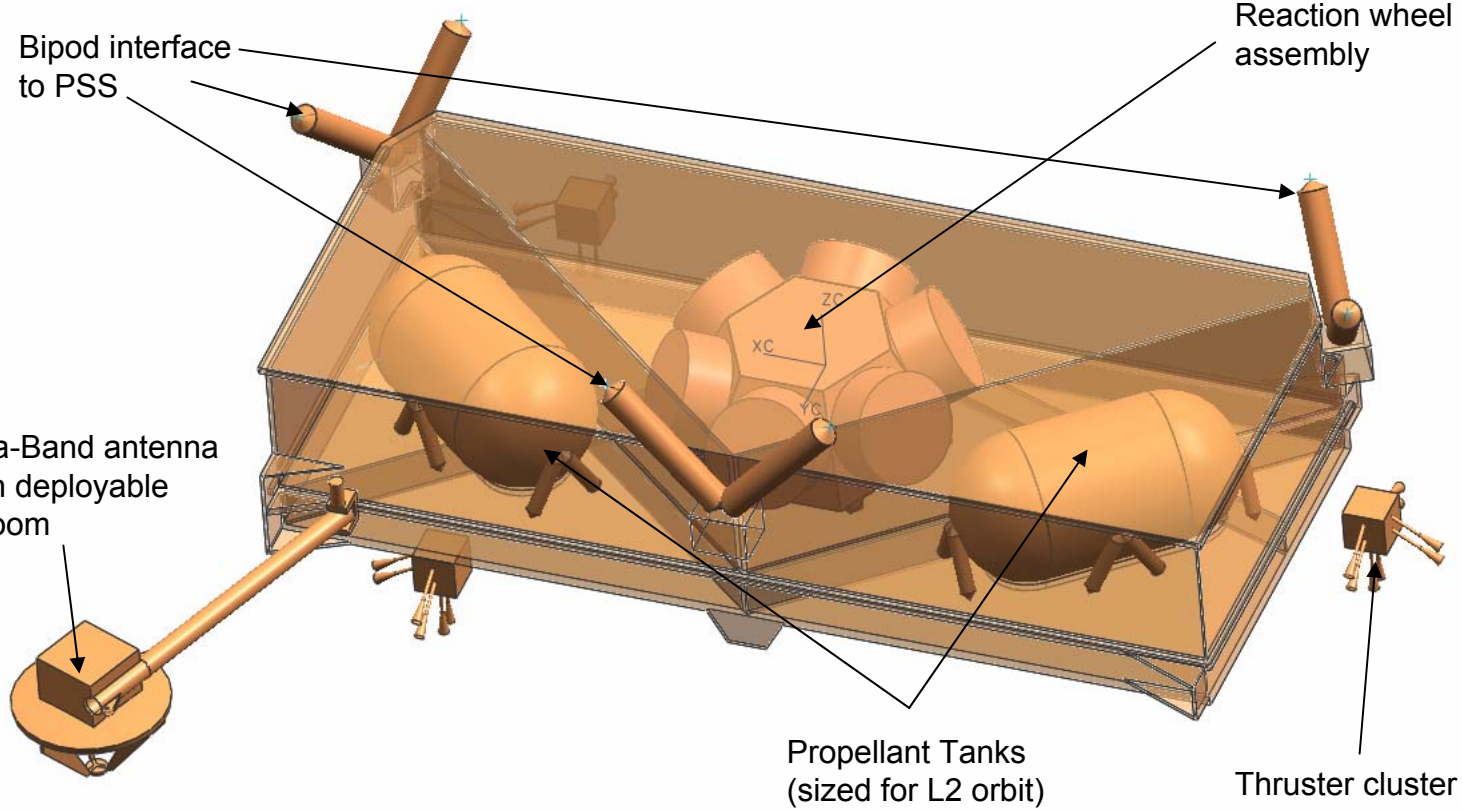
Placeholder Detector	Cooling power (assumed)
GAI	12 Watts
Detection	5 Watts
Characterization	8 Watts



Spacecraft Assembly

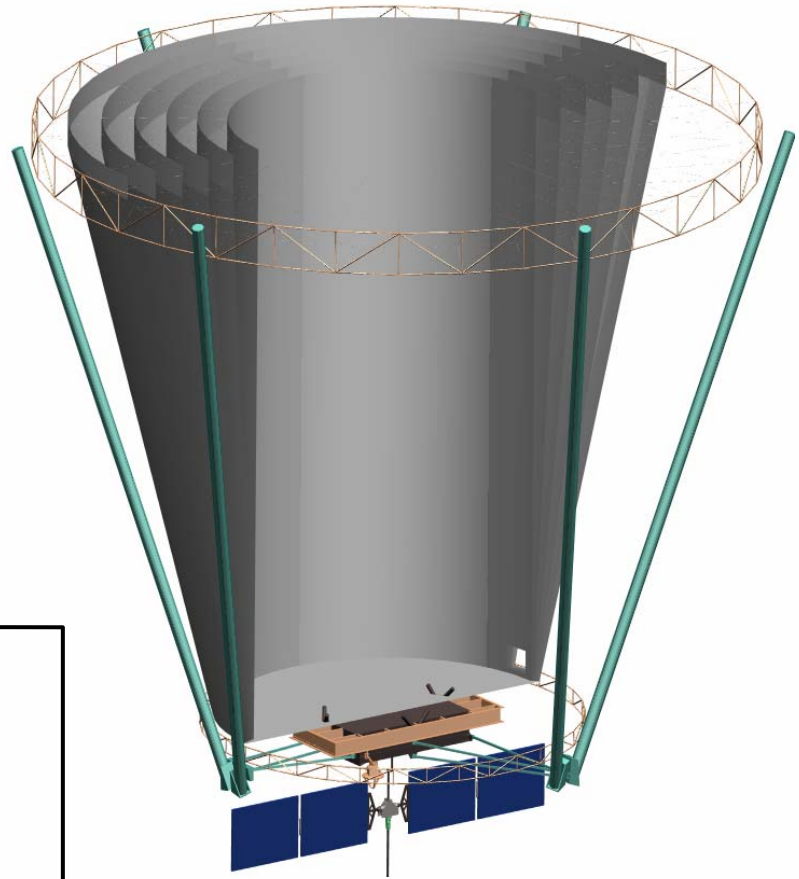
Spacecraft Bus

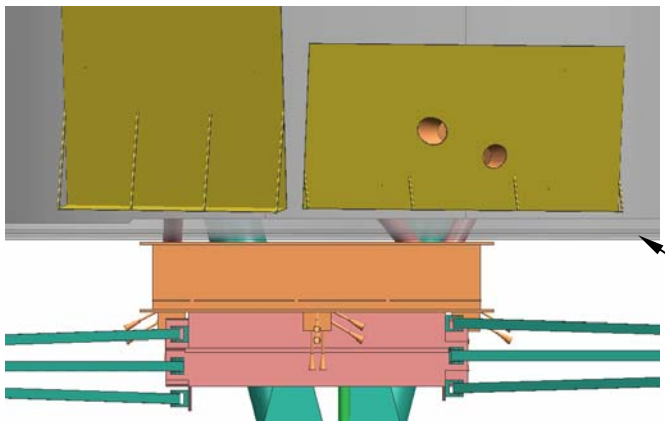
- Spacecraft houses the reaction wheels and propellant tanks
- Supports thrusters, antenna, v-groove system, solar array and solar sail
- In the load path for launch



V-groove

- V-groove is supported off the spacecraft bus
- Extendible booms are deployed and supported on tripod structures
- Perimeter trusses support the ends of the v-groove
- 6 layers separated by 3 degrees between layers and 50mm separation at base

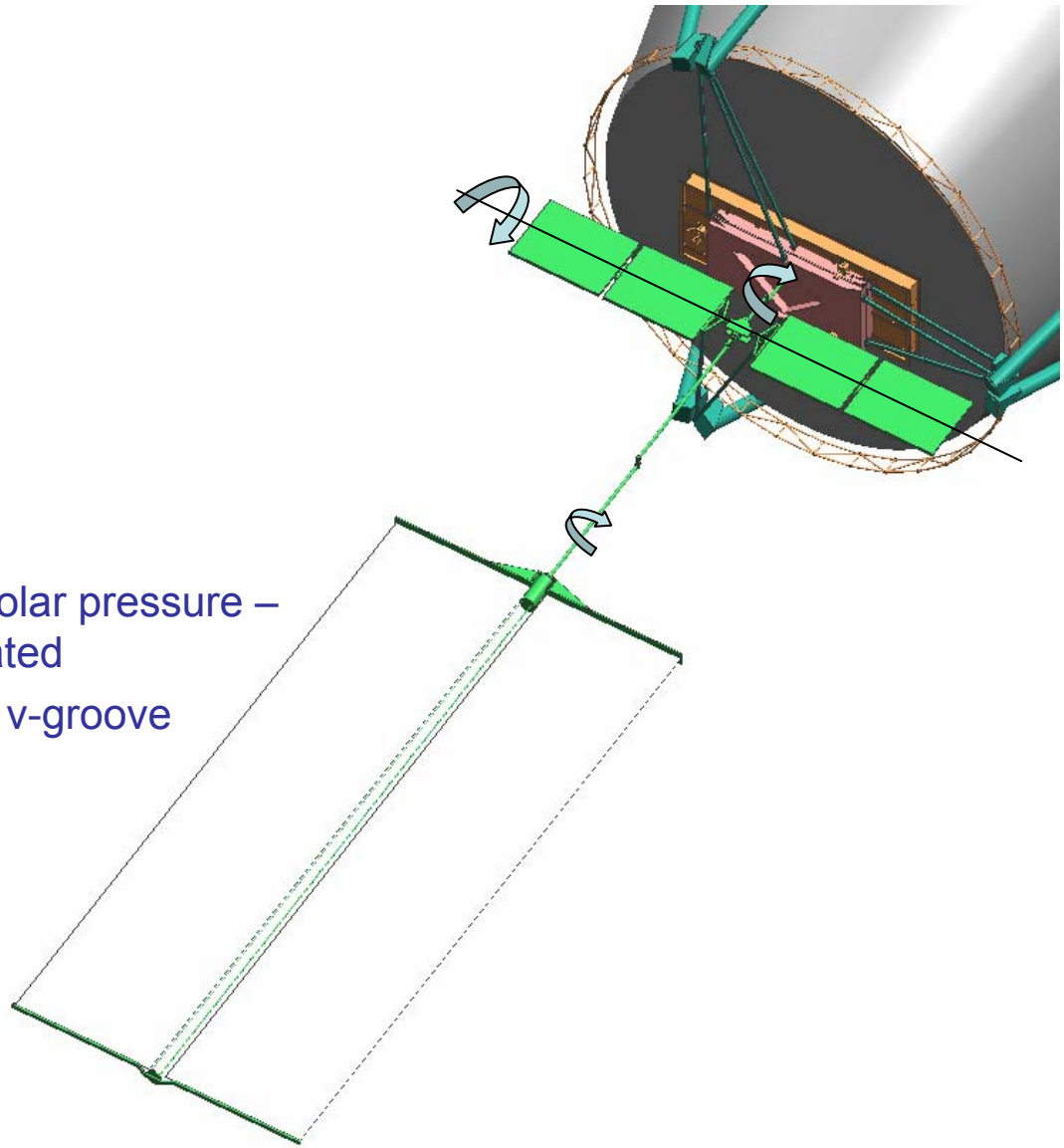




V-GROOVE CLOSEOUT:
6 flat layers occupy 50mm in height – remaining gap left for blanketing

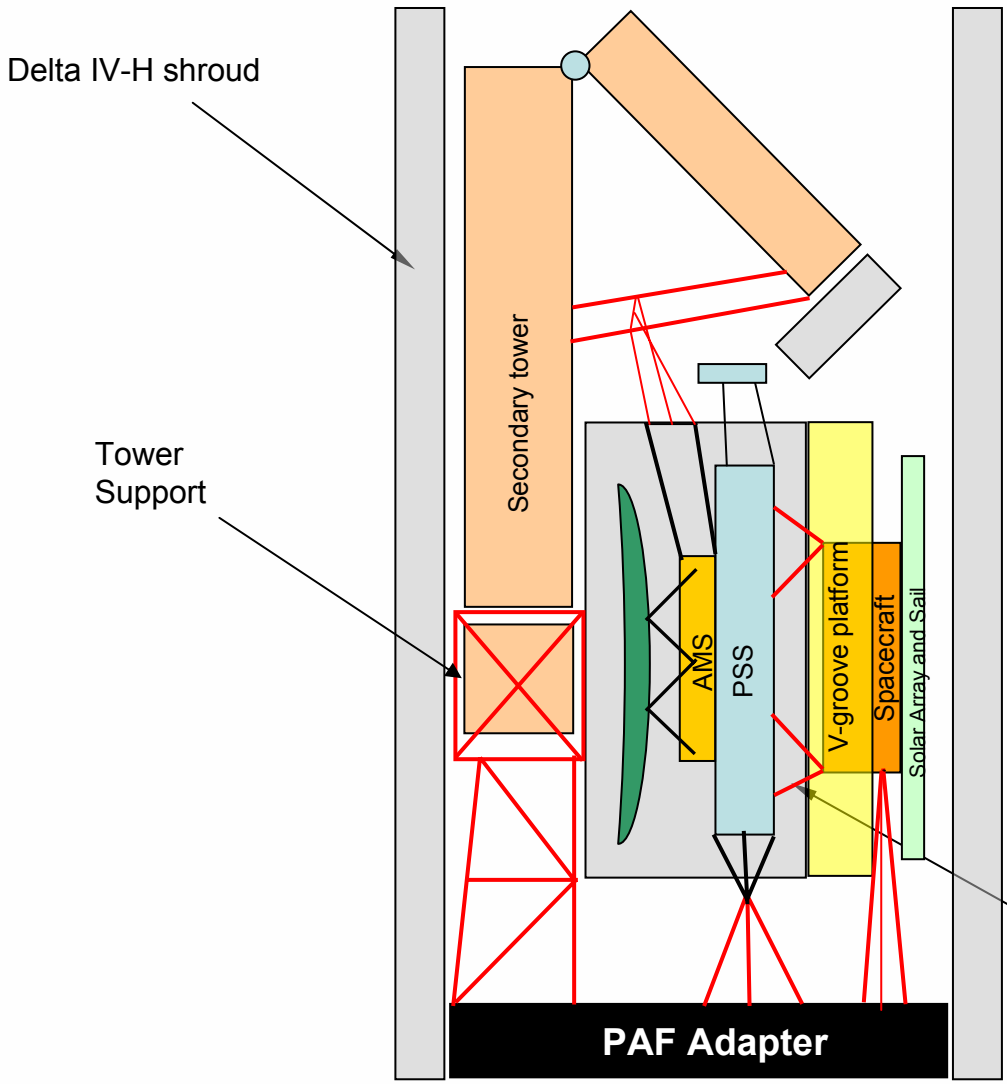
Solar Array and Sail

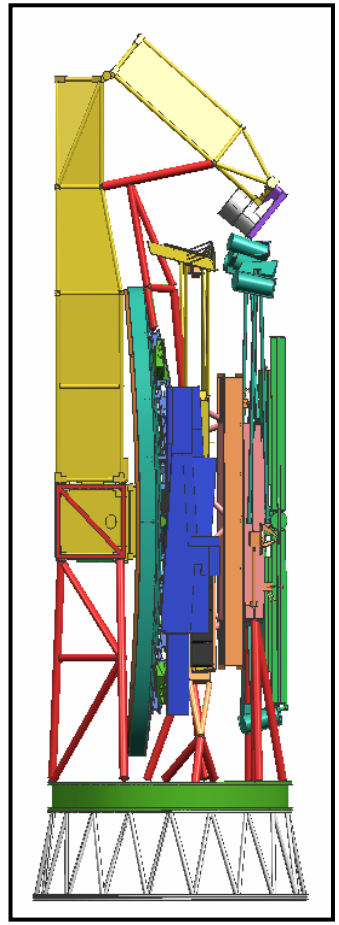
- Solar array
  - Panel size: 2m x 1.5m
  - Total area: 12 m^2
  - Power: 3000 W
  - 2 DOF
- Solar Sail
  - Length: 14 m
  - Width: 6.36m
  - 1 DOF
- Both are utilized to balance solar pressure – distances and lengths calculated
- Sail centerline is aligned with v-groove centerline



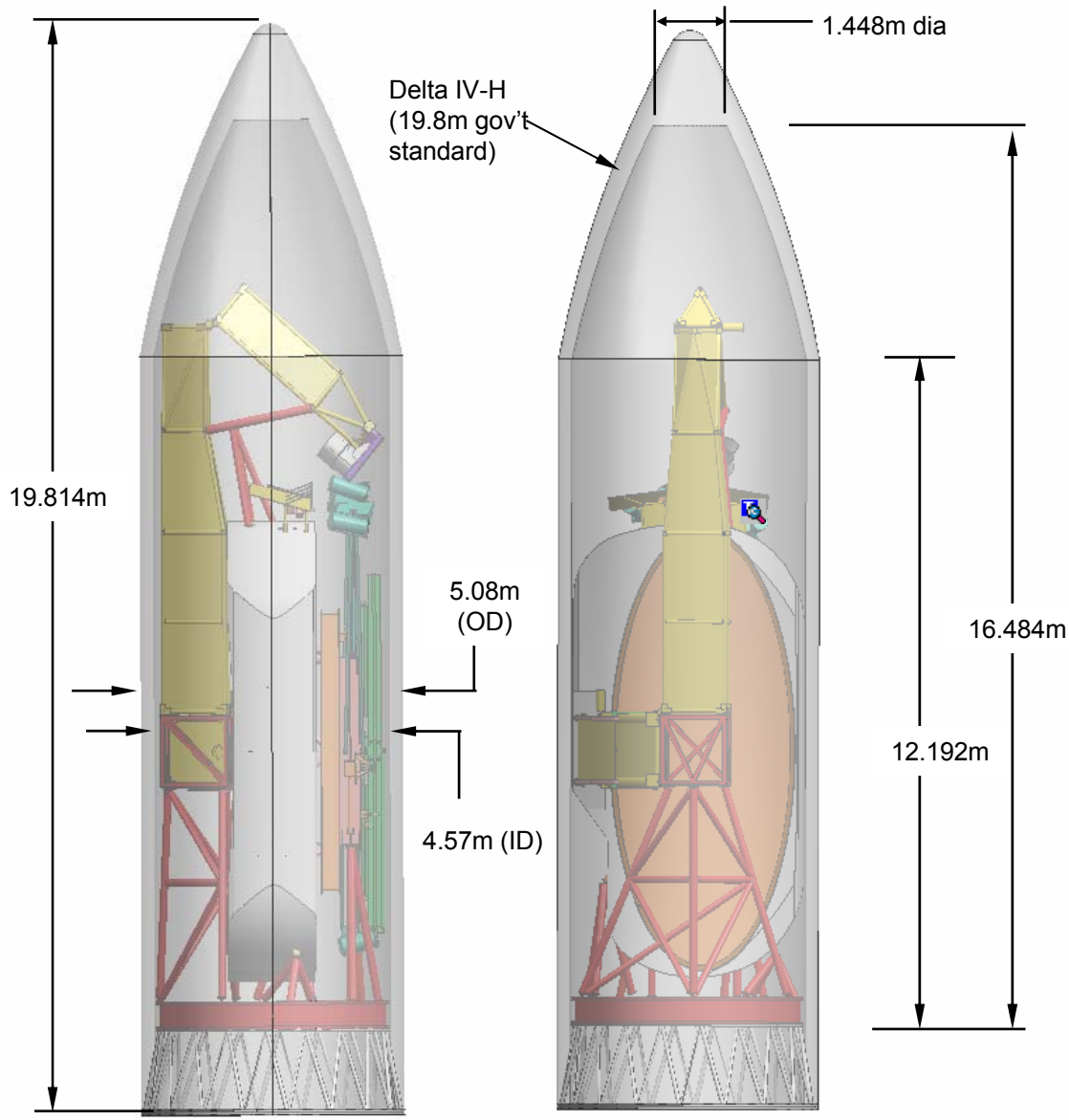
Stowed Launch Configuration

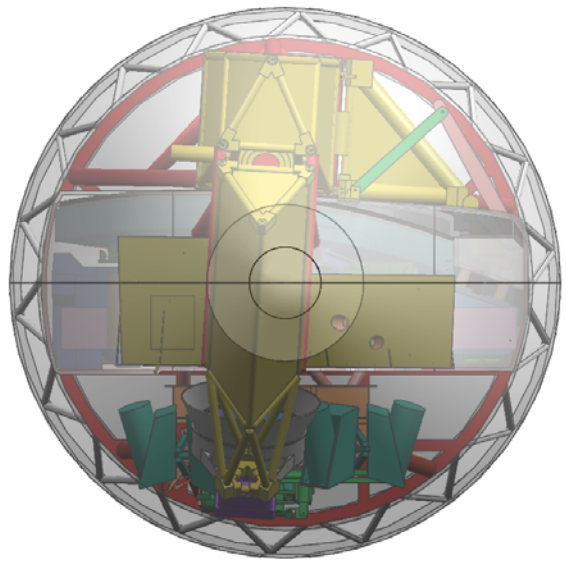
Launch Load Path Schematic





Stowed Configuration in Shroud





Note: Thermal enclosure shown transparent

Summary

- Many different concerns were considered throughout the design
  - CG and CP
  - Vibration isolation interface
  - Assembly integration and accessibility
  - Stowed configuration
  - Thermal and structural concerns
- Launch shroud diameter limits the stack-up height of components

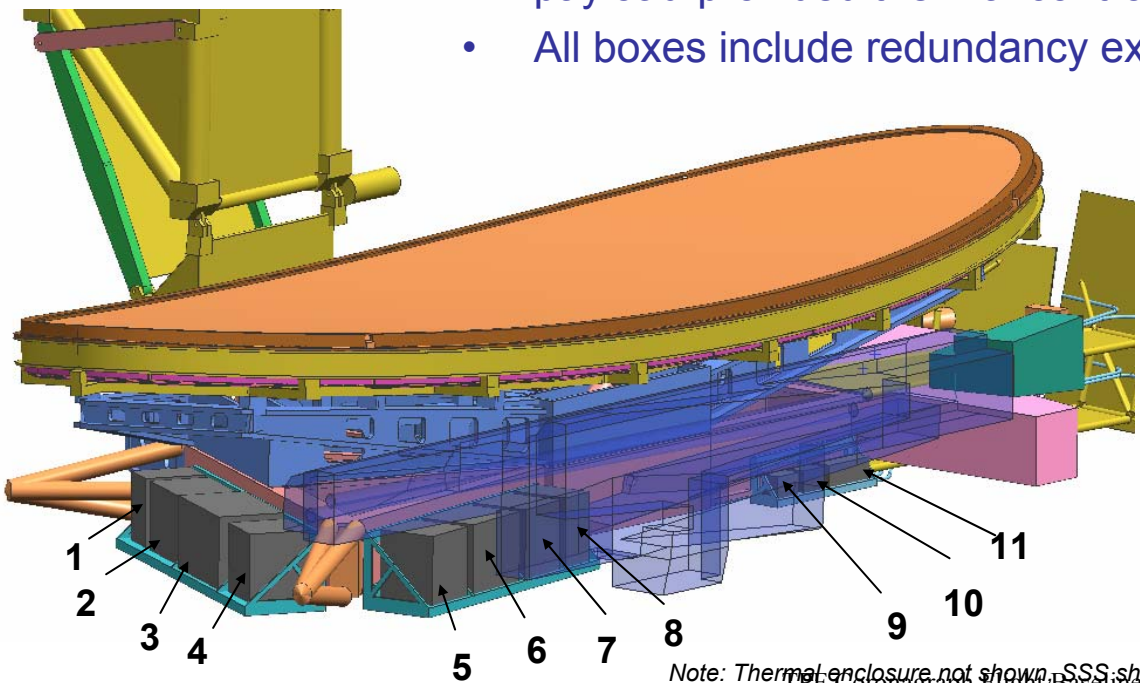
Back up slides

Payload Computing and Electronics Philosophy

Assumed Electronic box sizes: (W x H x L) cm

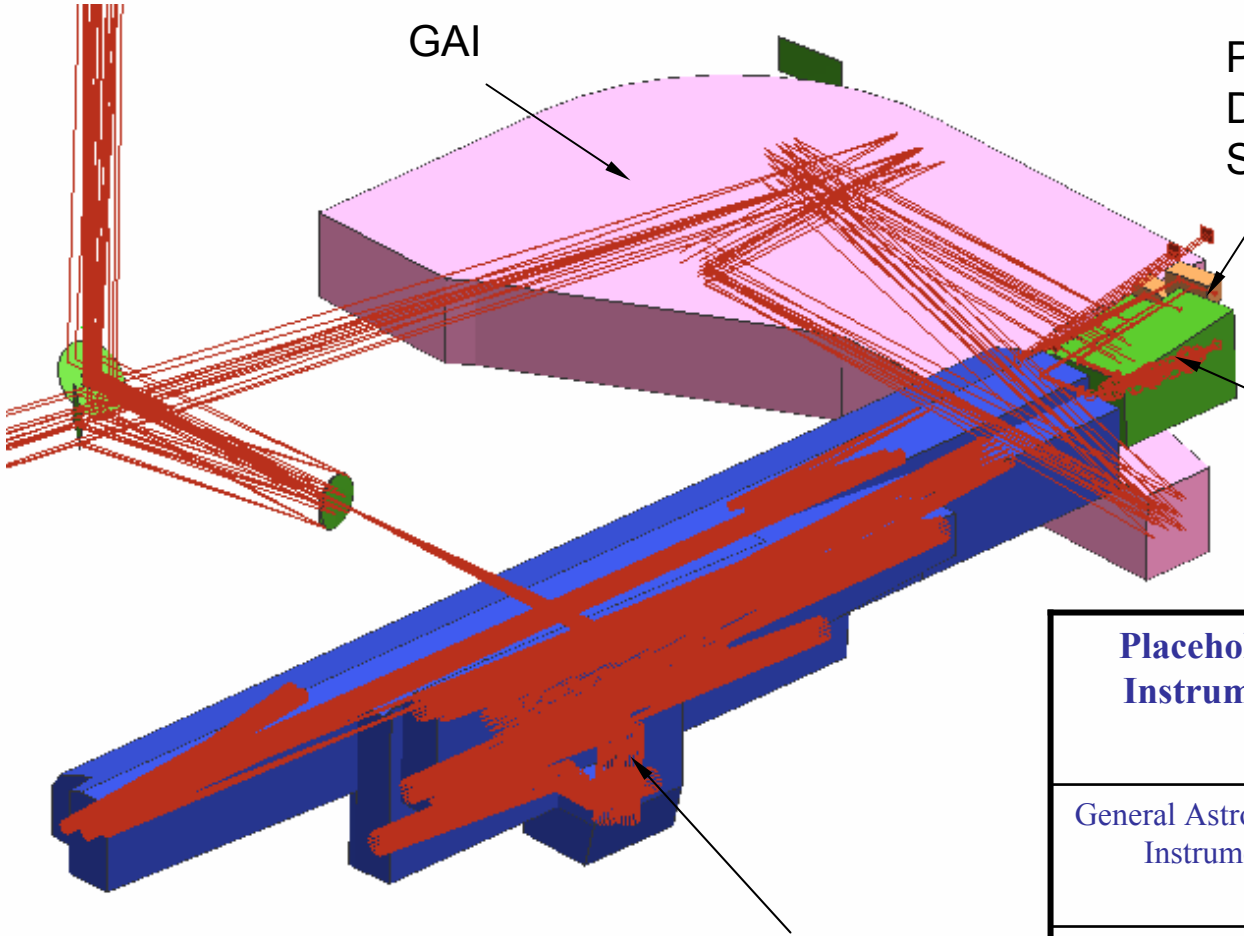
1) **OTA MCE - 36 x 38 x 24**
2) **Payload System Elex – 36 x 38 x 48**
3) **Laser Metrology – 40 x 40 x 68**
4) **OTA Thermal Control – 36 x 38 x 38**
5) **Planet characterization – 36 x 38 x 36**
6) **Planet detection – 36 x 38 x 48**
7) **Fine DM controller – 36 x 38 x 36**
8) **GAI – 36 x 38 x 24**
9) **Planet Detection Detector electronics– 12 x 12 x 18**
10) **Planet Characterization Detector electronics– 12 x 12 x 18**
11) **GAI Detector electronics– 12 x 12 x 36**

- Instruments responsible for science data computing including data compression
- Spacecraft will provide data storage and downlink
- All instrument electronics mounted on payload side to minimize cabling stiffness (thus dynamic perturbation exchange)
- Instrument electronics not required to be co-located with optics assemblies mounted on payload-provided thermal control plate
- All boxes include redundancy except for the GAI



Note: Thermal enclosure not shown, SSS shown transparent blue

Placeholder Instrument Beam Paths

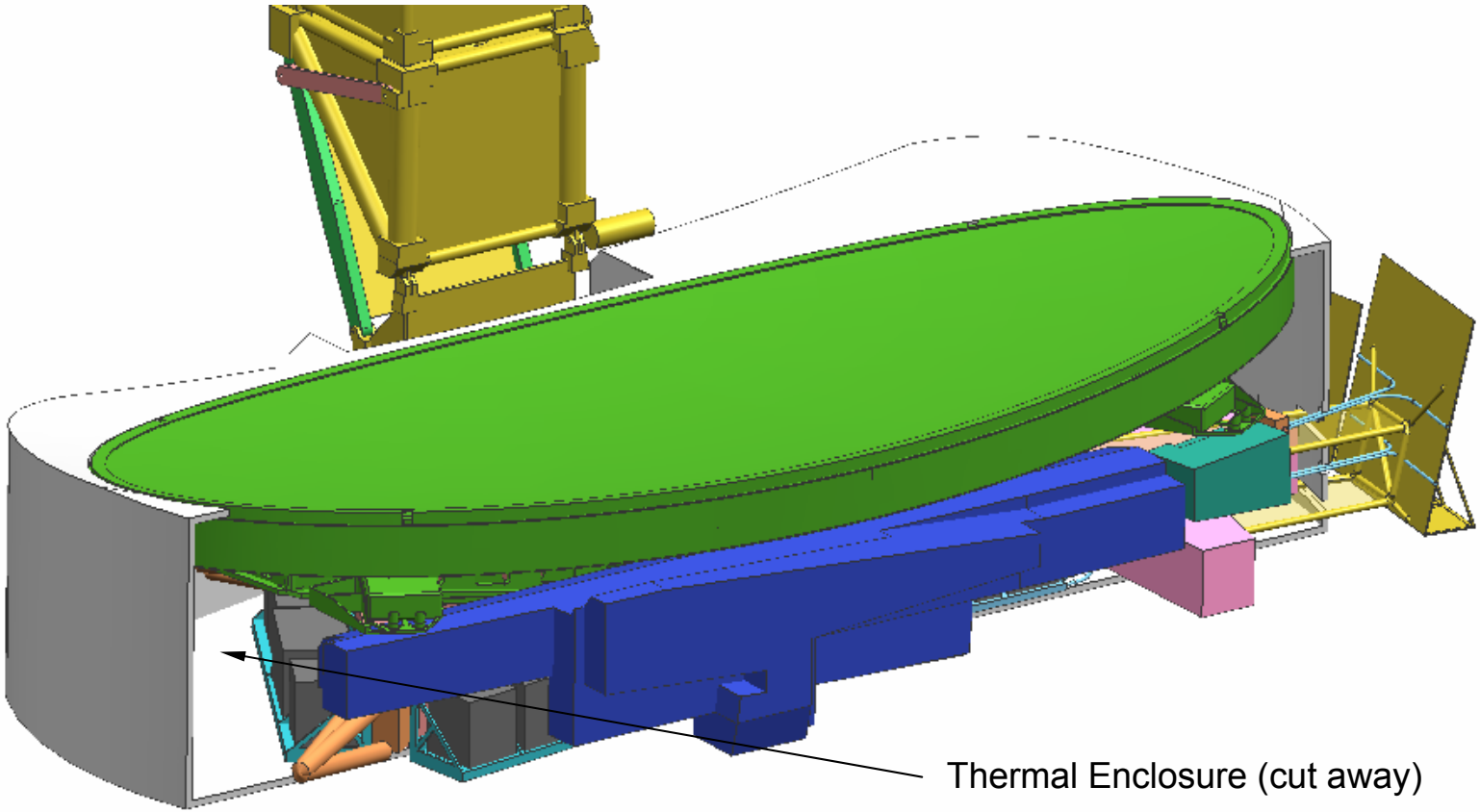


Placeholder Instrument	Placeholder Volume (millimeters)
General Astrophysics Instrument	2250 x 1400 x 400
Planet Detection Camera	325 x 400 x 300
Planet Characterization Instrument	750 x 400 x 300

Notes:
1) Beam paths highlighted in red

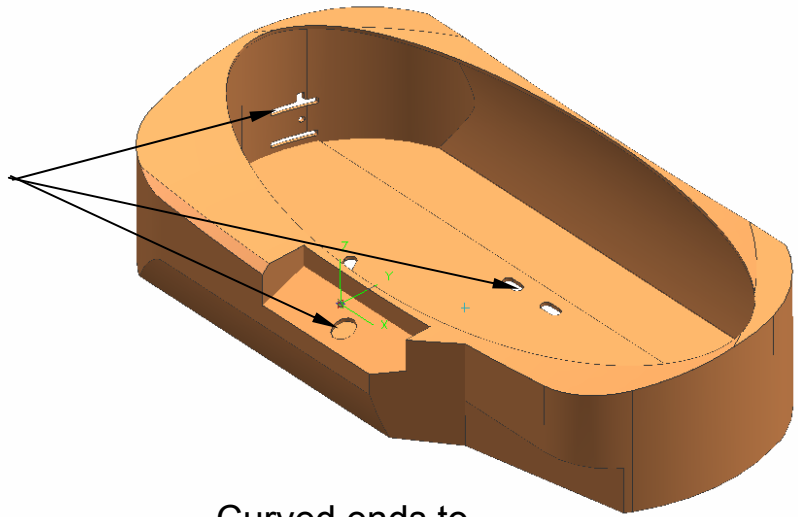
Thermal Enclosure

- The thermal enclosure completely surrounds the primary mirror and encloses everything behind the mirror.
- Maintains a stable temperature within the cavity
- Attaches to PSS.
- Cutouts for light beam, spacecraft interface, SM tower, and radiator support structure



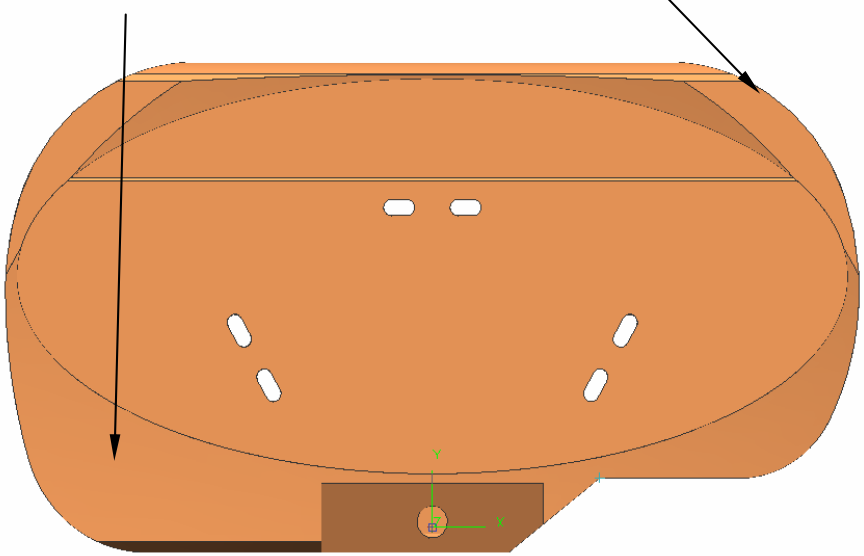
Thermal Enclosure Details

Cutouts for light beam, spacecraft interface, SM tower, and radiator support structure

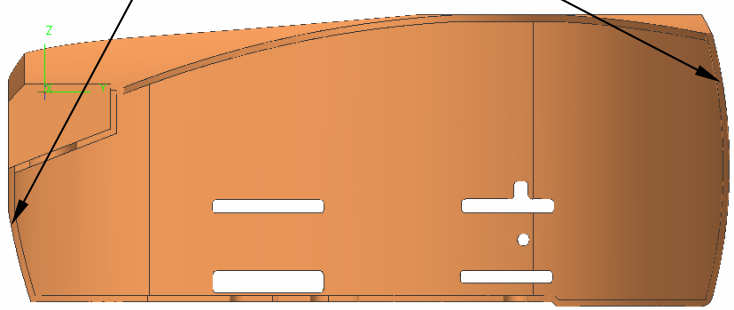


Rounded corners follow the v-groove

GAI requires larger volume

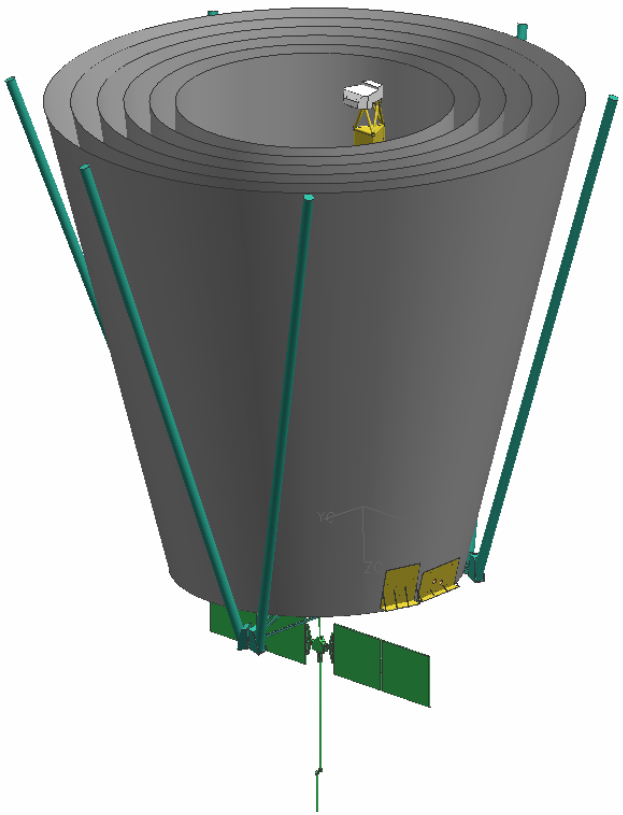


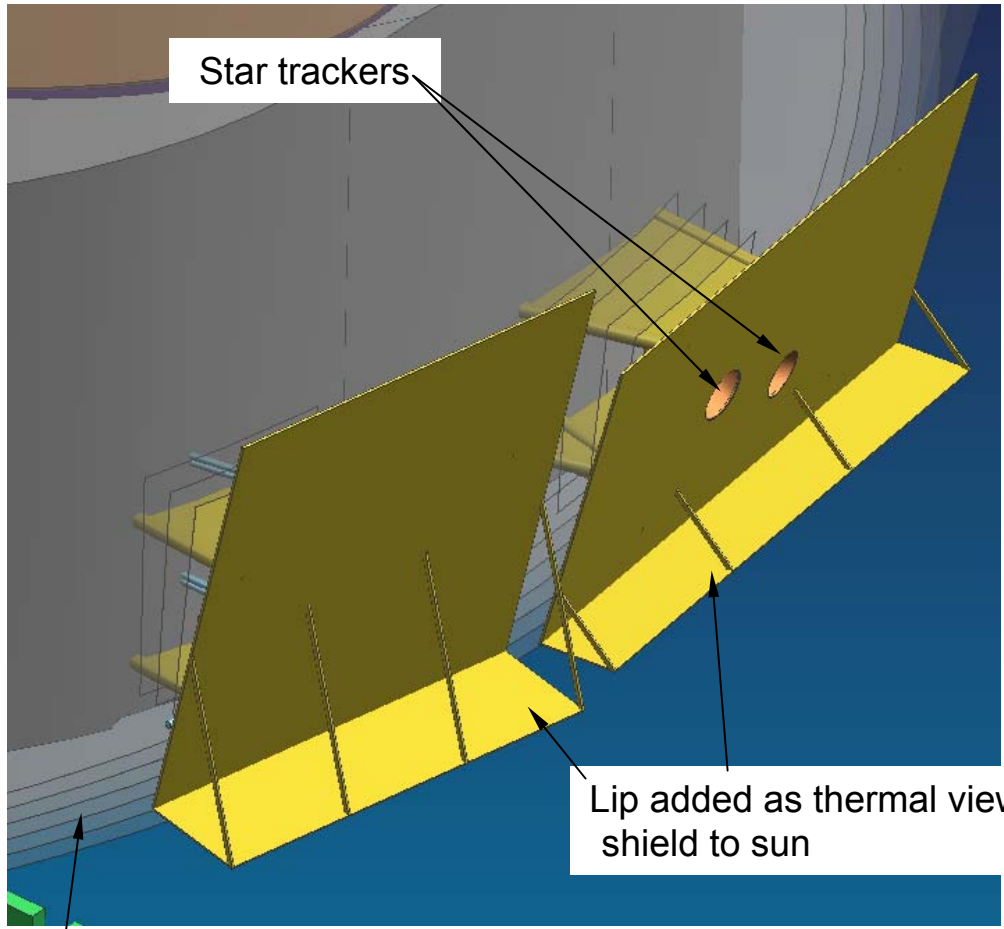
Curved ends to follow the launch shroud



X-section

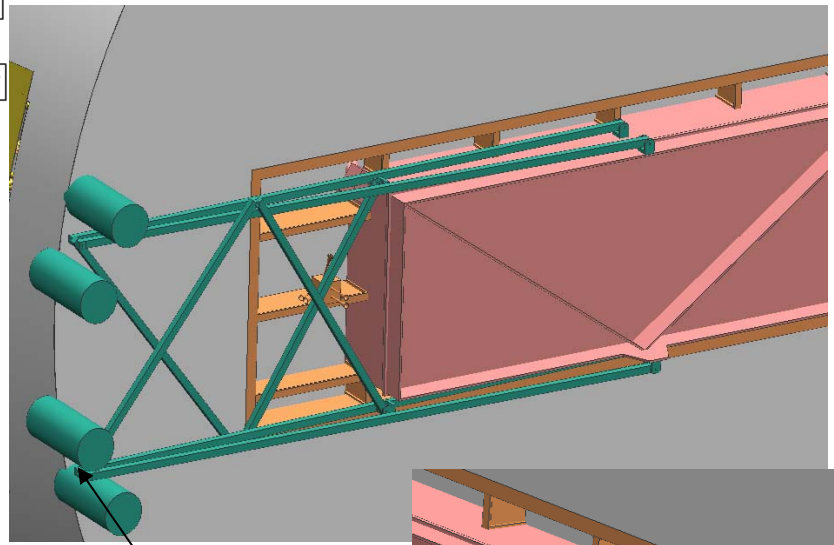
Radiator locations outside v-groove



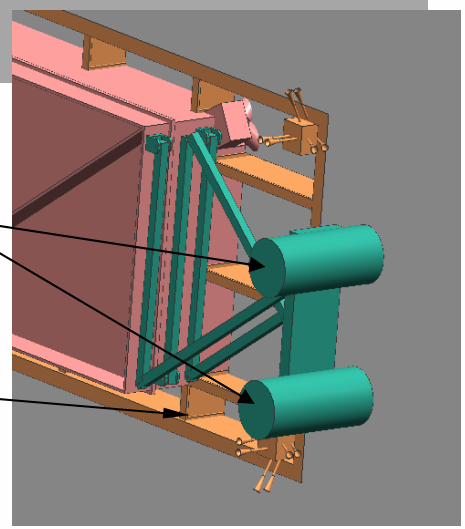


V-groove deployment canister details

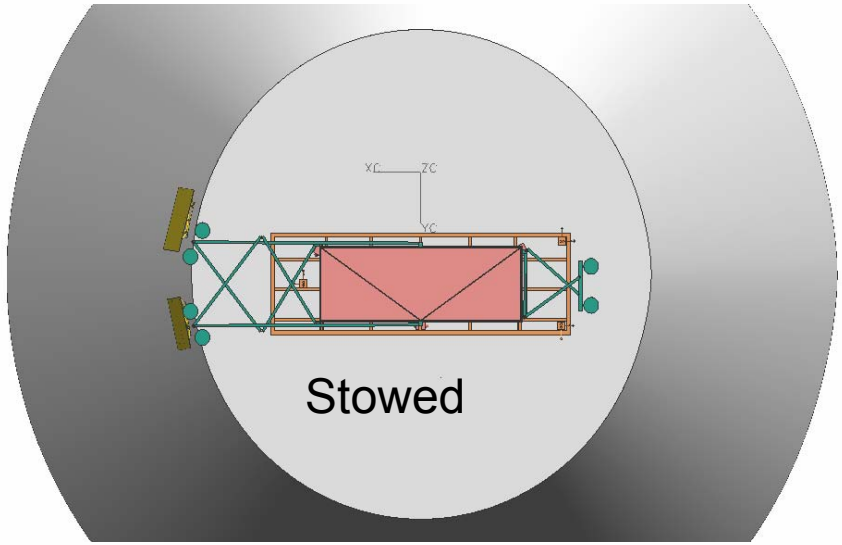
- Canister deployment similar to JWST secondary deployment

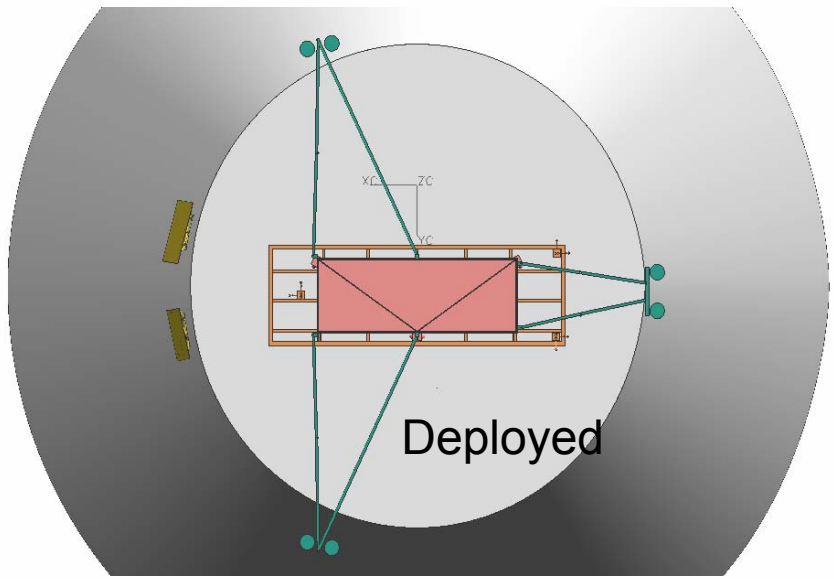


Two canisters supported at ends of each tripod

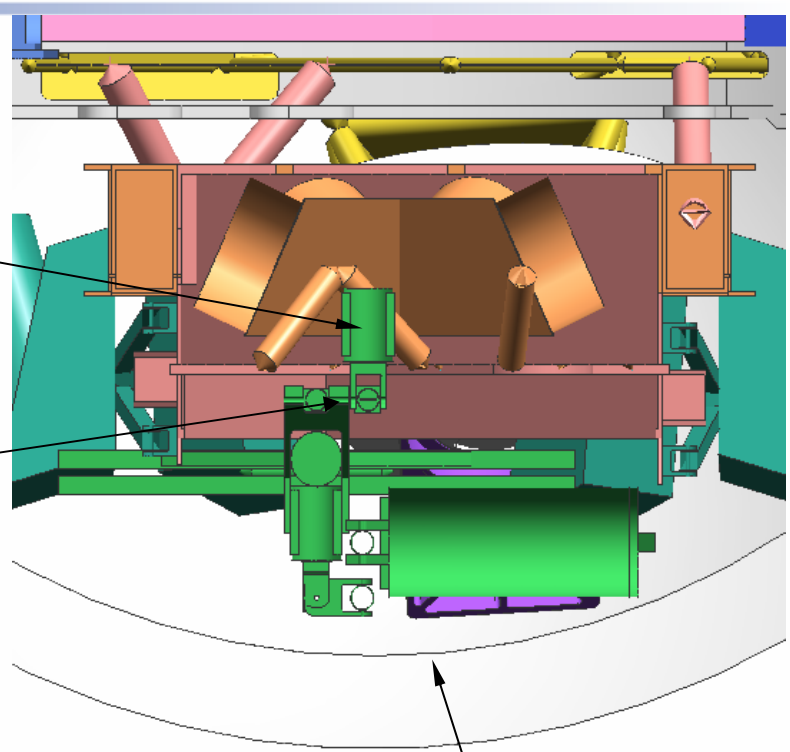


V-groove stowed support frame with panel closeouts – also supports thrusters and launch locking of deployment mechanisms



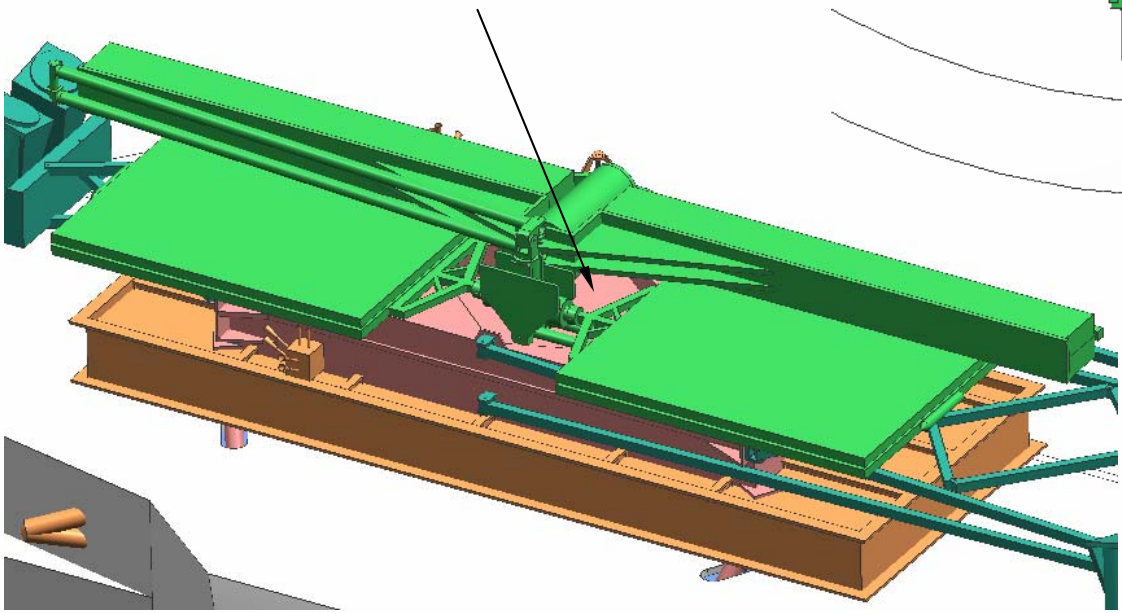


Solar Array and Sail Stowed



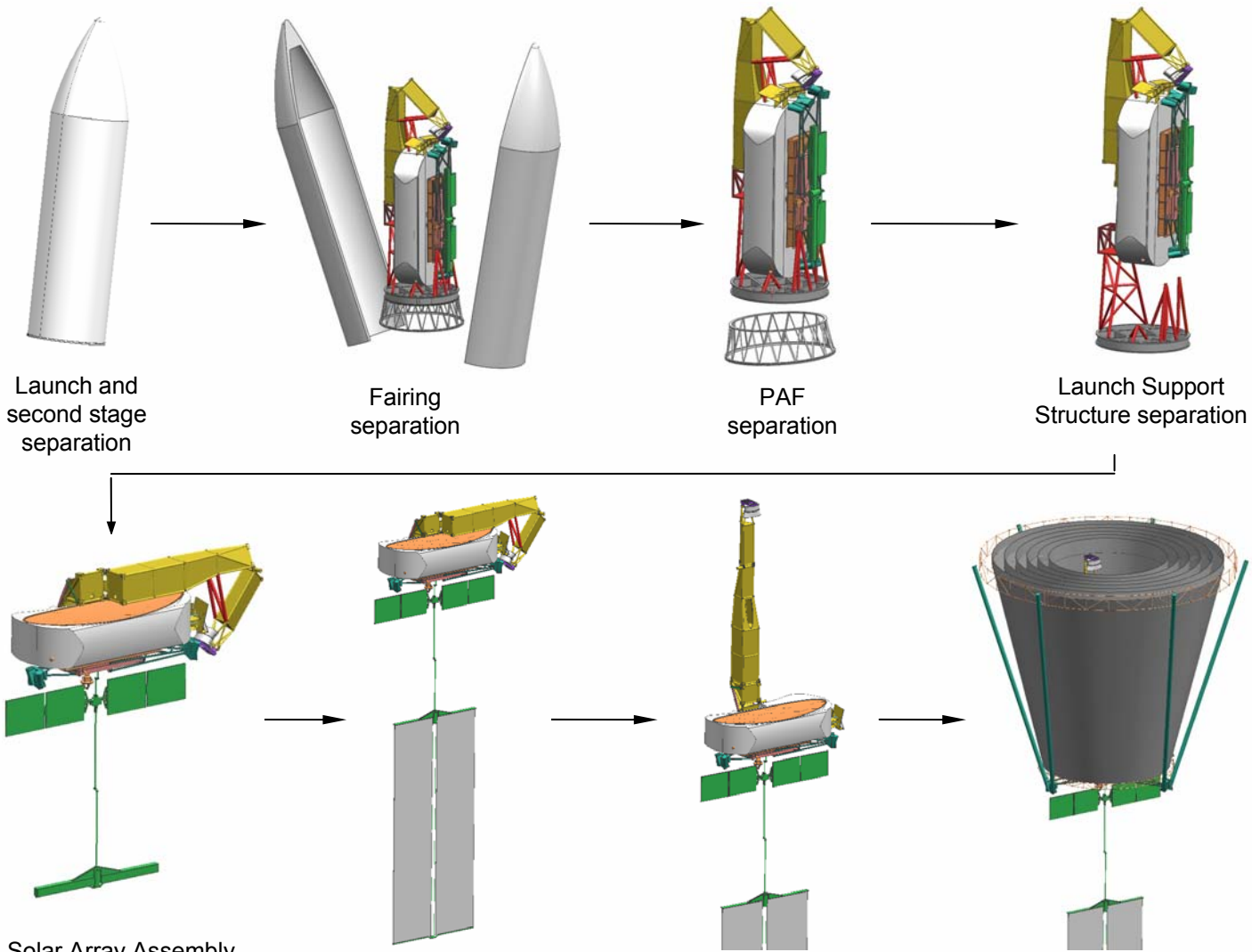
Motor within spacecraft

Recess in spacecraft allows SA deployment boom to stow



Inner diameter of launch shroud

Deployment Sequence



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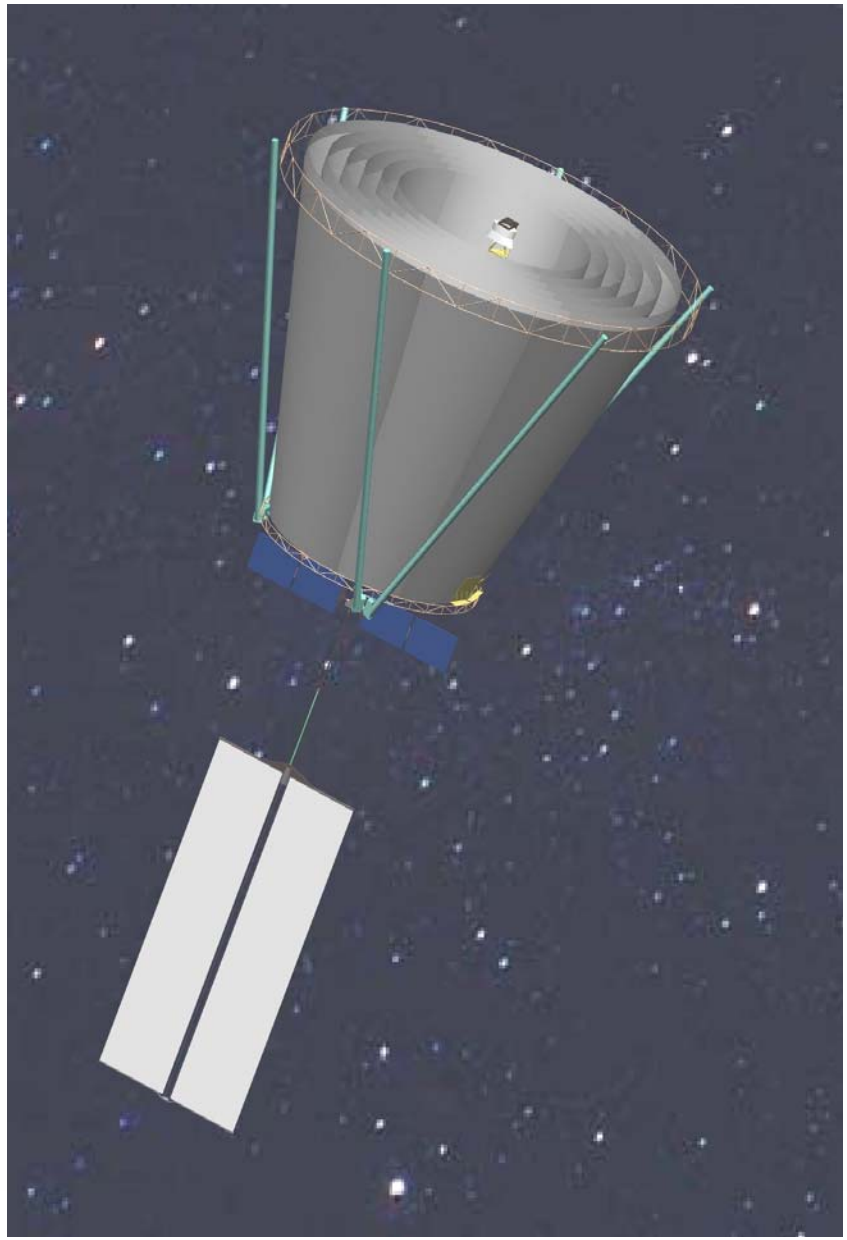
TPF Terrestrial Planet Finder

OTA Mechanical Design and Configuration FB1

Charles Engler
Electromechanical Systems
GSFC

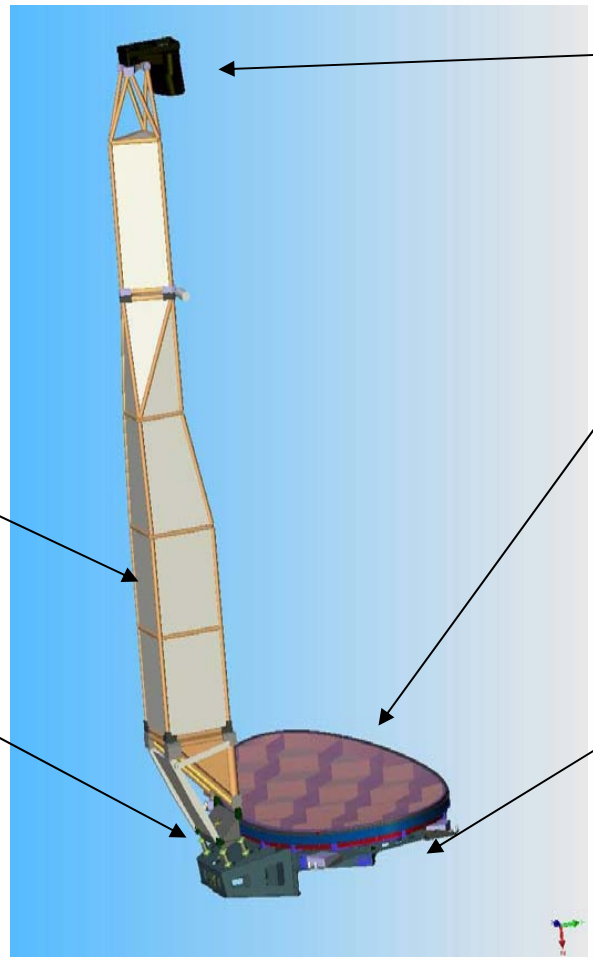
Contributors:
Jeff Guzek
-Design Interface Inc.

11-12 July 2005



Optical Telescope Assembly FB1

- Major subassemblies



Secondary Mirror Assembly
- .9m x .4m Secondary Mirror
- Pointing and control system
- Thermal control system

Primary Mirror Assembly
- 8mx3.5m Mirror
- Thermal control system
- Cover deployment system

Deployable Tower
- 4 segment
- M55J composite

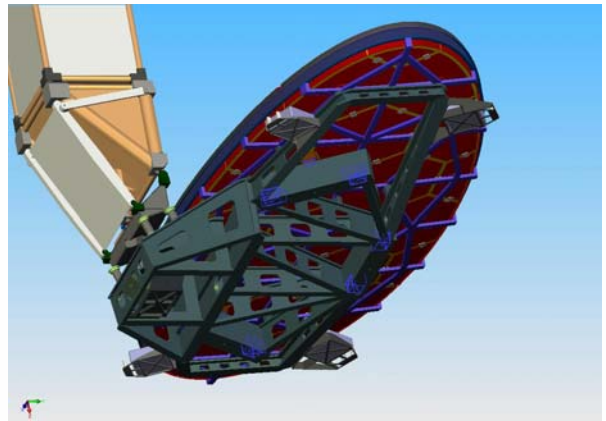
Third Mirror Assembly
- .3mx.3m Mirror
- Pointing and control system
- Thermal control system

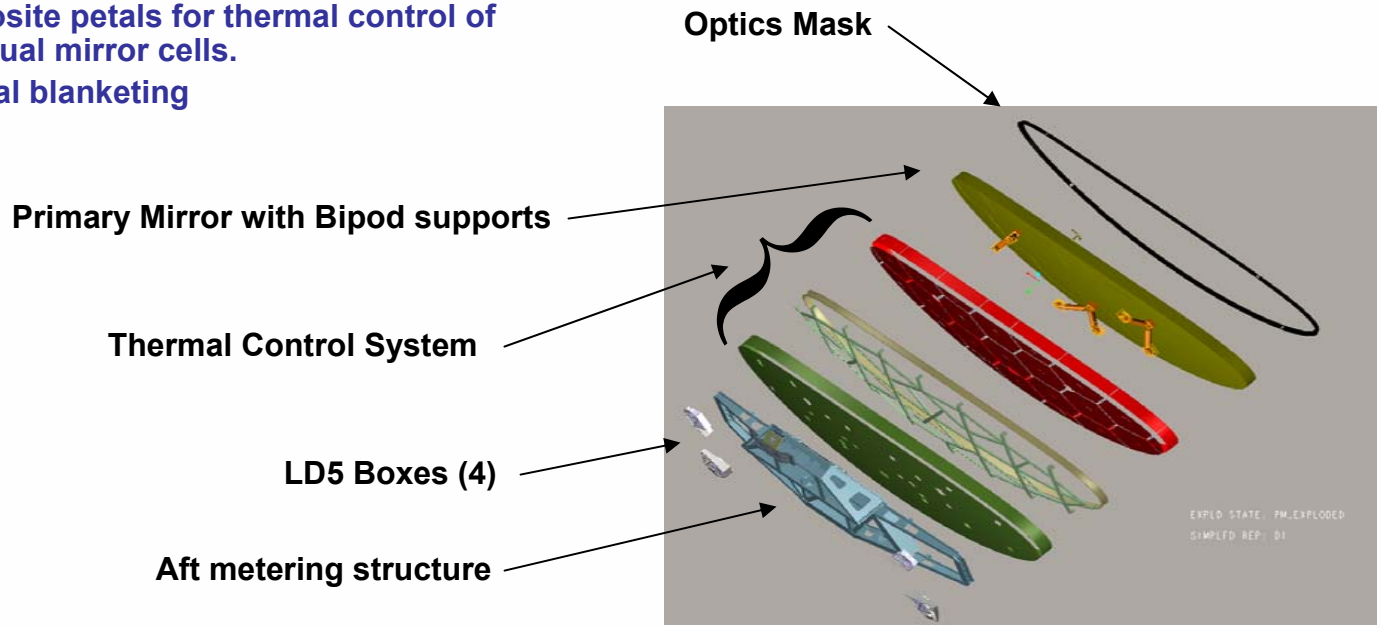
Aft Metering Structure
- Meters focal distance of PM, SM, M3
- Support thermal control system

Primary Mirror Assembly FB1

- Estimated Mass FB1: 2626 Kg
- 8m x 3.5m Primary Mirror 1065kg
- Aft metering structure
  - M55J Composite material
  - Supports (meters) PM,SMA,M3
  - PM bipod structure
  - LD5 Box support

- PM thermal control system
  - Composite Rib Structure supporting PM thermal control system.
  - Composite petals for thermal control of individual mirror cells.
  - Thermal blanketing





Secondary Mirror Assembly FB1

- Estimated weight FB1: 146 Kg

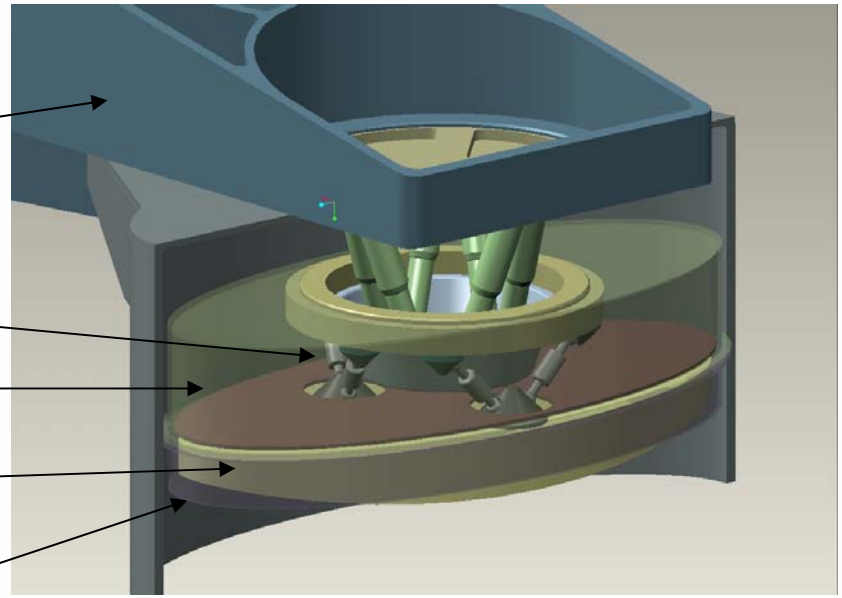
SM support structure to tower

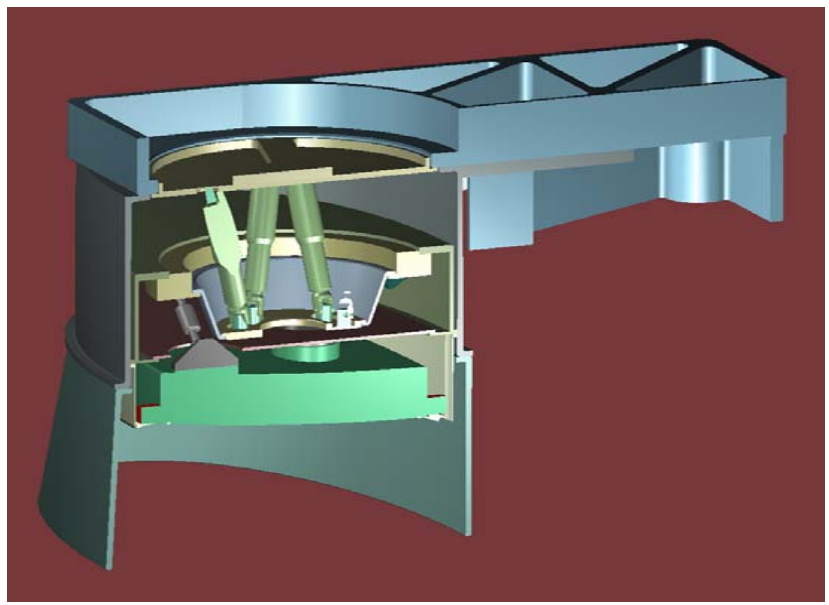
Three Bipod supports minimize stresses into mirror

Mirror thermal control system

.9m x .4m Secondary Mirror
17.7 Kg (70% light weighted)

Optical mask

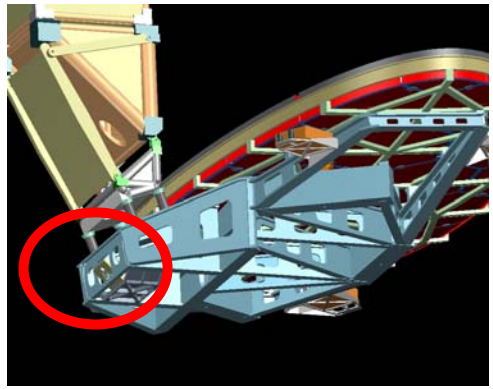




Mirror pointing and control system
- Two-stage hexapod
- Coarse stage:
  - Travel: +/- 25mm
  - Repeatable: +/- 100 nanometers
- Fine stage:
  - Stroke: +/- 200 nanometers
  - Resolution: TBD

M3 Mirror Assembly FB1

- Estimated weight FB1: 20 Kg



Optical mask

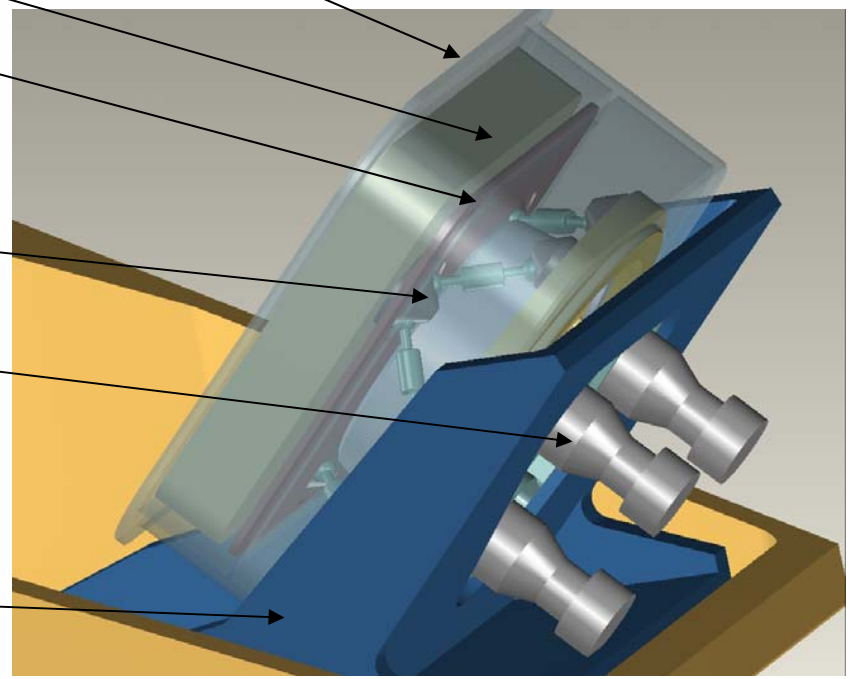
.3m x .3m Tertiary mirror
5 Kg (50% light weighting)

Mirror thermal control system

Three Bipod supports minimize stresses into mirror

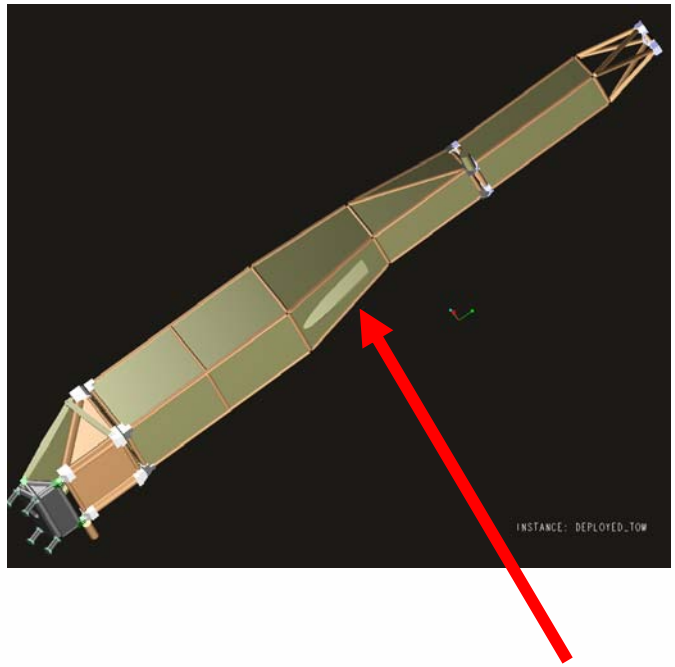
Mirror pointing & control system
- Tip,Tilt, Focus mechanism
- Rubicon-type actuator
  - 6 mm stroke, 9 nm resolution

Support Cradle to AMS



Secondary Tower FB1

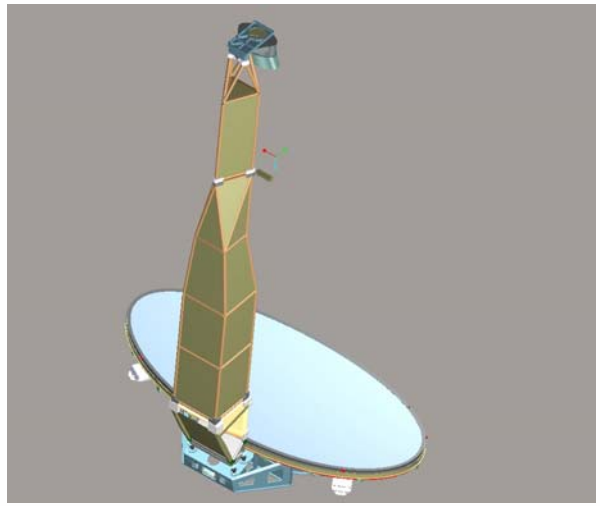
- Estimated mass FB1: 197 Kg
- Metering structure featuring a 12m deployable boom
- Four segments deploy from stow position and lock after deployment
- Composite truss configuration
- Provision for accommodating the Optics Path through the lower half of the assembly

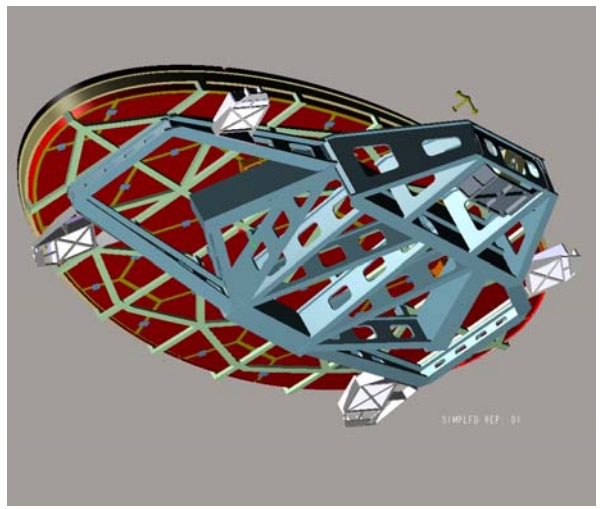


Optics Path

Summary- OTA Mechanical Configuration FB1

- Integrated team approach:
  - **GSFC Thermal, Optical, Structural and Systems involvement**
  - **GSFC and JPL mechanical design collaboration**
- Established working concepts for all major subassemblies
- Solid FB1 development efforts will result in substantial improvements to the OTA for FB2





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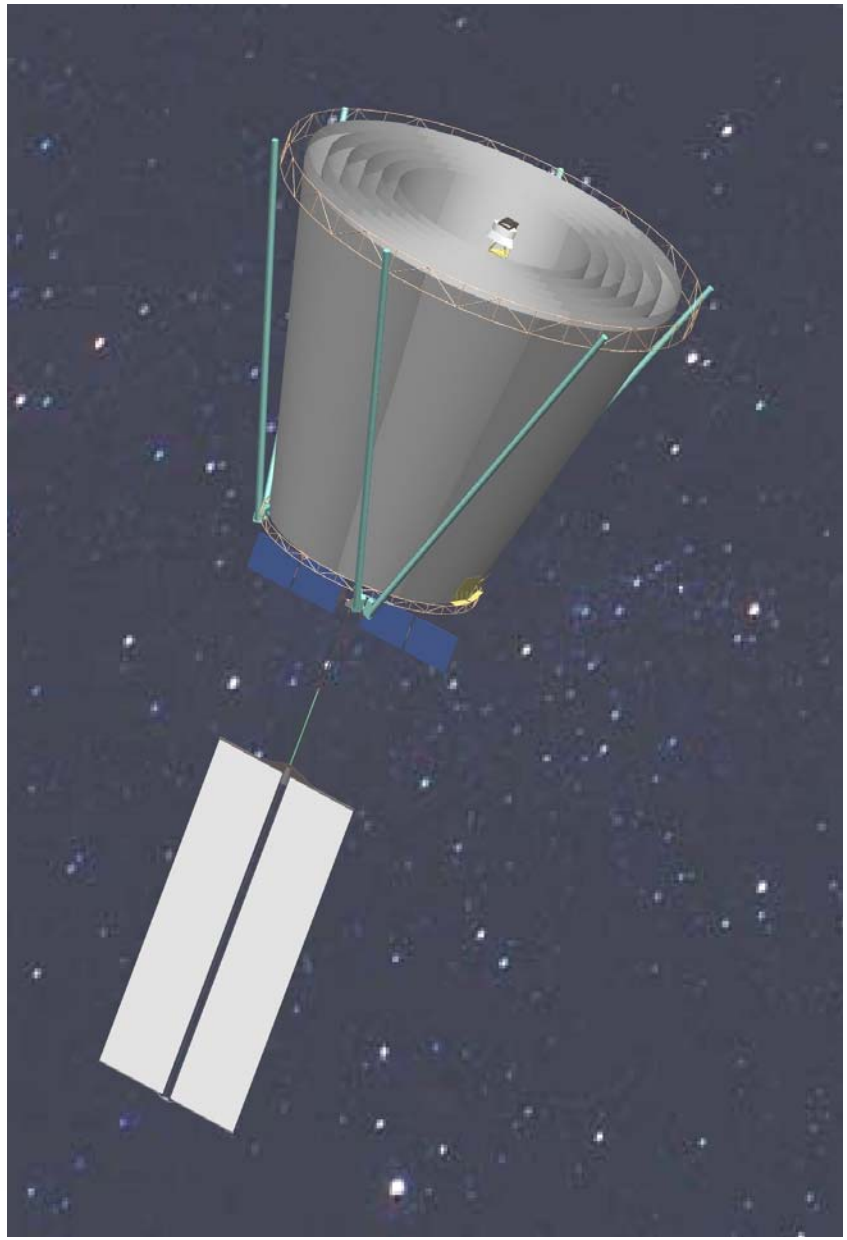
TPF Terrestrial Planet Finder

System Thermal Architecture and Design

Terry Cafferty
TC Technology

Contributor: Eug Kwack

11-12 July 2005



Thermal Control Architecture Topics

1. the thermal challenge of TPF-Coronagraph
   - extreme dimensional stability for long periods with a moving Sun
2. observation scenario drives thermal architecture
   - summarize observation scenario and how it determines thermal reqmts
3. baseline overall thermal design approach
   - cocoon V-groove shield, nested boxes, cold biasing, potential for active control
4. we limit where the Sun can be
   - stray light, thermal stability, and passive cooling enabled
5. the V-groove sunshade
   - ‘removing the Sun’, features, operating principles, options
6. behind the primary mirror
   - nested components, thermal damping, active control potential, power dissipation
7. electronics cooling
   - electronics thermal pallet, isolation, heat pipes, radiator, active option
8. detector cooling
   - ~ -100 C, ethane heat pipes, shielded cold radiator, active option

The TPF-Coronagraph Thermal Challenge

- milli-Kelvin or better temperature stability
- many-hour observation
- 30-degree dither
  (moves the Sun midway through the total observation)

- cooling for instrument detectors at ~ -100 C
- cooling for observatory electronics
- cooling for science instruments

- control transient thermal inputs
- control internal power fluctuations
- limit active thermal control system instabilities
- control spacecraft thermal transients

The Observation Sequence

defines the primary task of the thermal control system

1. slew observatory to acquire new target

2. settle into thermo-mechanical equilibrium in a fixed clocking orientation about the boresight axis
   - quick settling is good (maximizes observation time)

3. correct wavefront with deformable mirror(s)

4. build up initial image (in thermally stable environment)

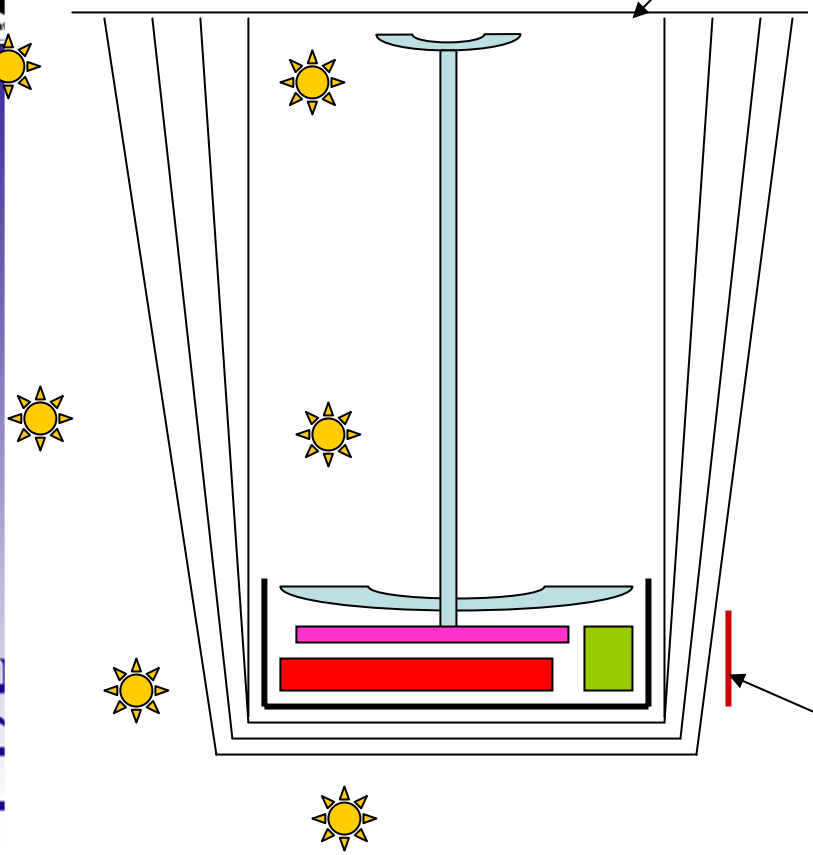
5. **dither 30 degrees about the boresight axis**
   - **Sun 'moves' 30 degrees**

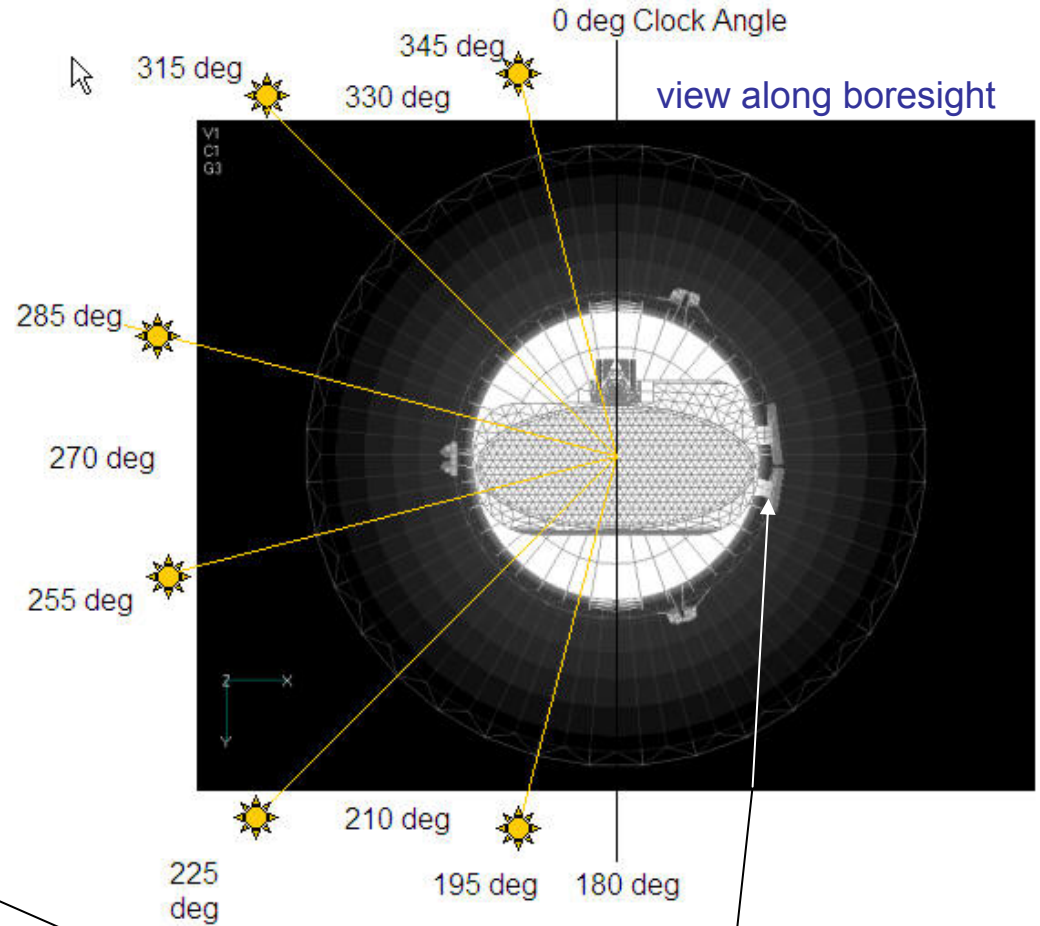
6. **build up speckle subtraction image**
   - **multiple hours in destabilized thermal environment**
   - **quick settling is potentially bad (conflict with step 2)**

Solar Position Restrictions

enable passive cooling and control solar stray light

Sun is kept behind this plane
for stray light and thermal control





Passive cooling radiators for
electronics and detectors

Overall Thermal Architecture

passive and active features combine to provide required thermal stability

primary mirror thermal control approach replicated for secondary mirror

optical baffle

6-layer V-groove thermal shield to 'remove' the Sun and provide cold bias even with direct Sun loading

Laser metrology system provides real-time compensation for rigid-body relative motion between primary and secondary mirrors

secondary mirror support tower cools to equilibrium inside MLI (black outer layer)

multi-zoned radiant heater plate maintains ULE primary mirror at temperature where CTE minimized

heated 'isothermal' enclosure

electronics and detector cooling radiators, fed by heat pipes

aft metering structure (AMS)

inside-to-out cold biasing provides opportunity for precision active thermal control

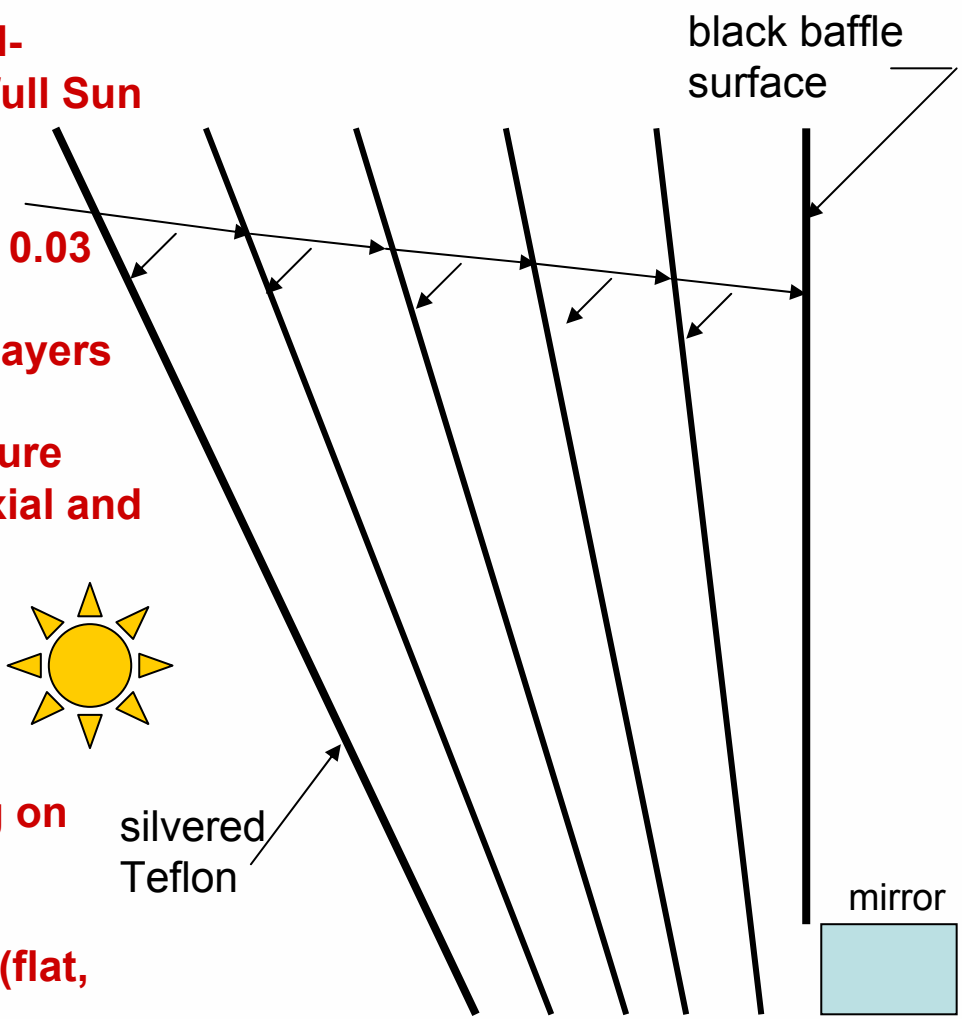
payload support structure (PSS)

spacecraft

Six-layer Conical V-groove Sunshield

critical to primary mirror thermal stability

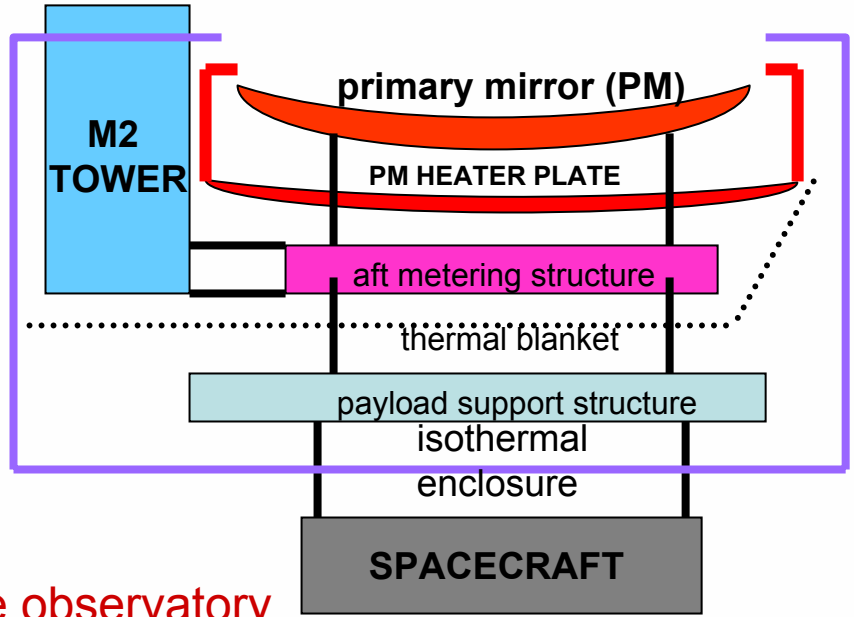
- outer surface silvered Teflon second-surface mirror, T ~ 220 K EOL max in full Sun
- intermediate surfaces IR-specular aluminum on Kapton film, emittance ~ 0.03
- 3 degrees axial divergence between layers
- 200 degree circumferential temperature difference in outer layer reduced by axial and circumferential radiant tunneling
- circumferential gradient at any axial position in baffle ~0.1 degree
- controls (transient) radiative loading on optically active side of primary mirror
- also considering alternative shapes (flat, 'sugar scoop') and active control on intermediate layer(s)



Behind the Primary Mirror

multiple features enhance thermal stability during long observations

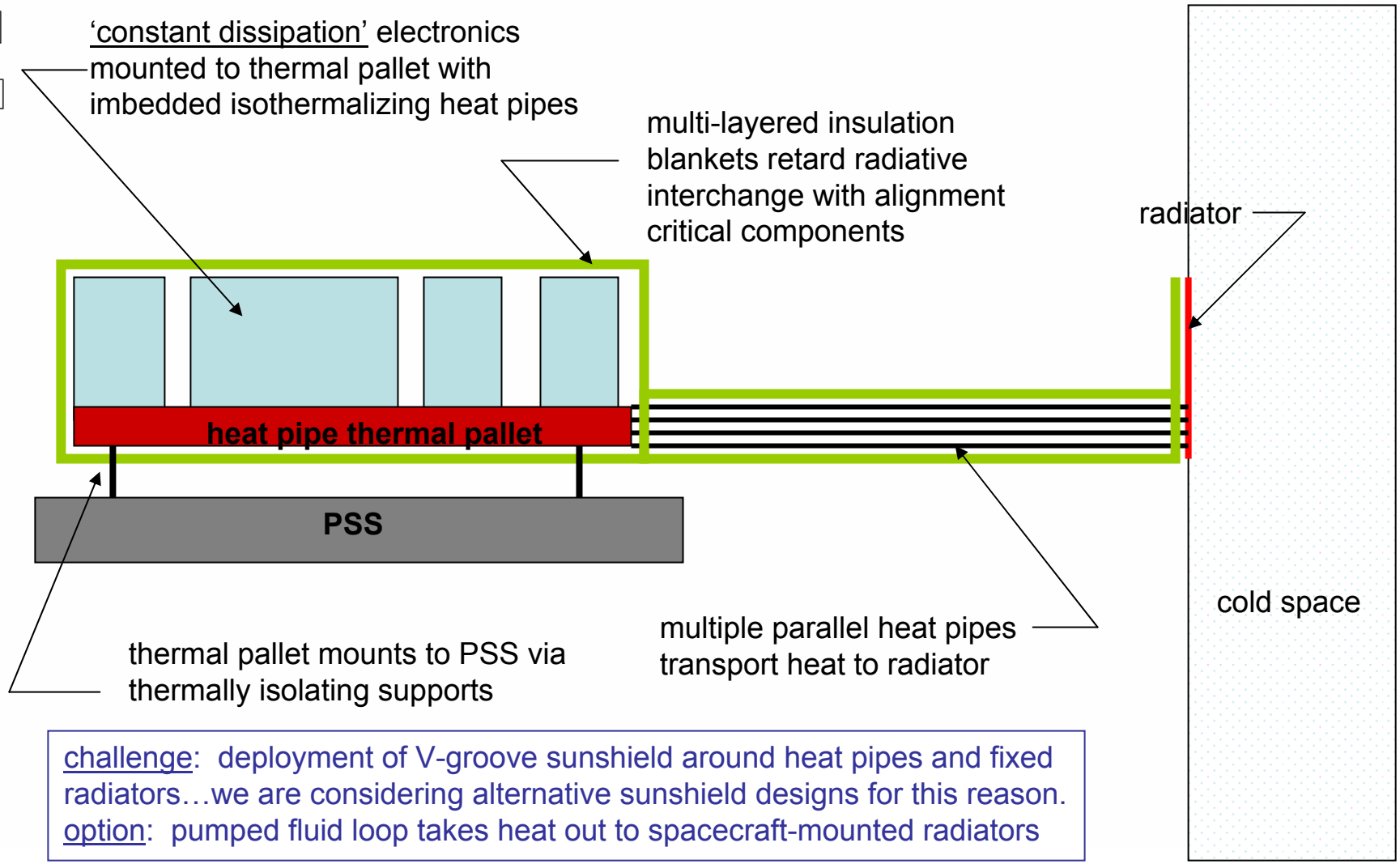
- primary mirror is heated radiatively by a multi-zoned heater plate…to a bulk temperature corresponding to minimal ULE CTE
- design is cold biased from the PM heater plate 'out', to provide active control authority over all elements



- spacecraft is cold biased relative to the observatory
- SM tower allowed to cool to equilibrium, inside its thermal blankets
- multi-layered insulation (MLI) at interface between AMS and PSS
- nested configuration provides natural damping of outside disturbances
- potential to selectively implement precision active thermal control (as suggested by detailed examination of transient thermal model output)

Payload Electronics Thermal Control

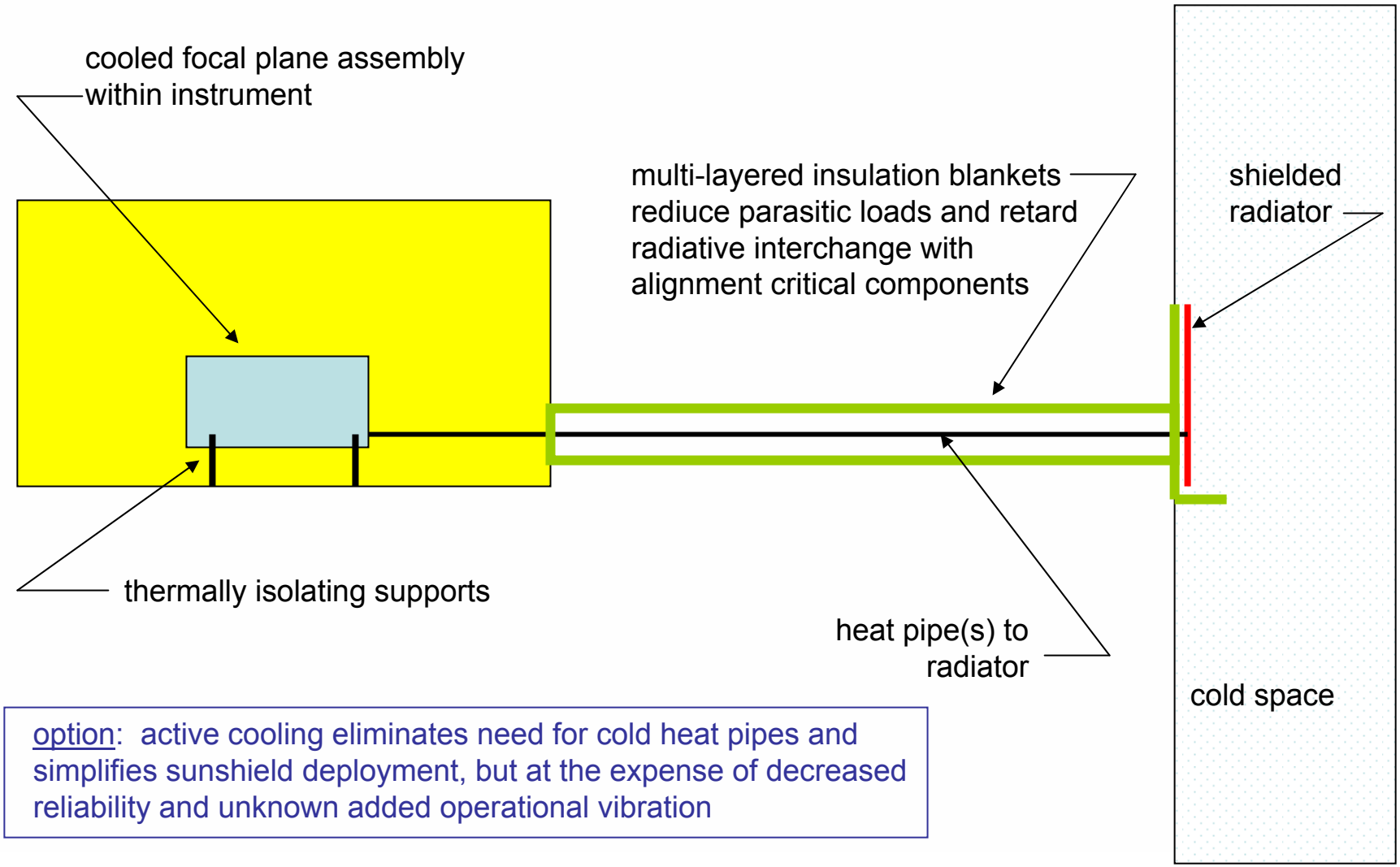
electronics heat sent via heat pipes to radiator on observatory cold side



challenge: deployment of V-groove sunshield around heat pipes and fixed radiators…we are considering alternative sunshield designs for this reason.
option: pumped fluid loop takes heat out to spacecraft-mounted radiators

Thermal Control for Science Detectors

detectors cooled to ~ 170 K by ethane heat pipes feeding a fixed radiator on observatory cold side



option: active cooling eliminates need for cold heat pipes and simplifies sunshield deployment, but at the expense of decreased reliability and unknown added operational vibration

Thermal Architecture and Design

summary

- we have a full array of design features available to us to provide the required thermal stability
- we now have a relatively detailed full system thermal model
- we are exercising that model in a logical fashion to evaluate performance and guide the implementation of design features
- we are confident we can provide the needed thermal stability

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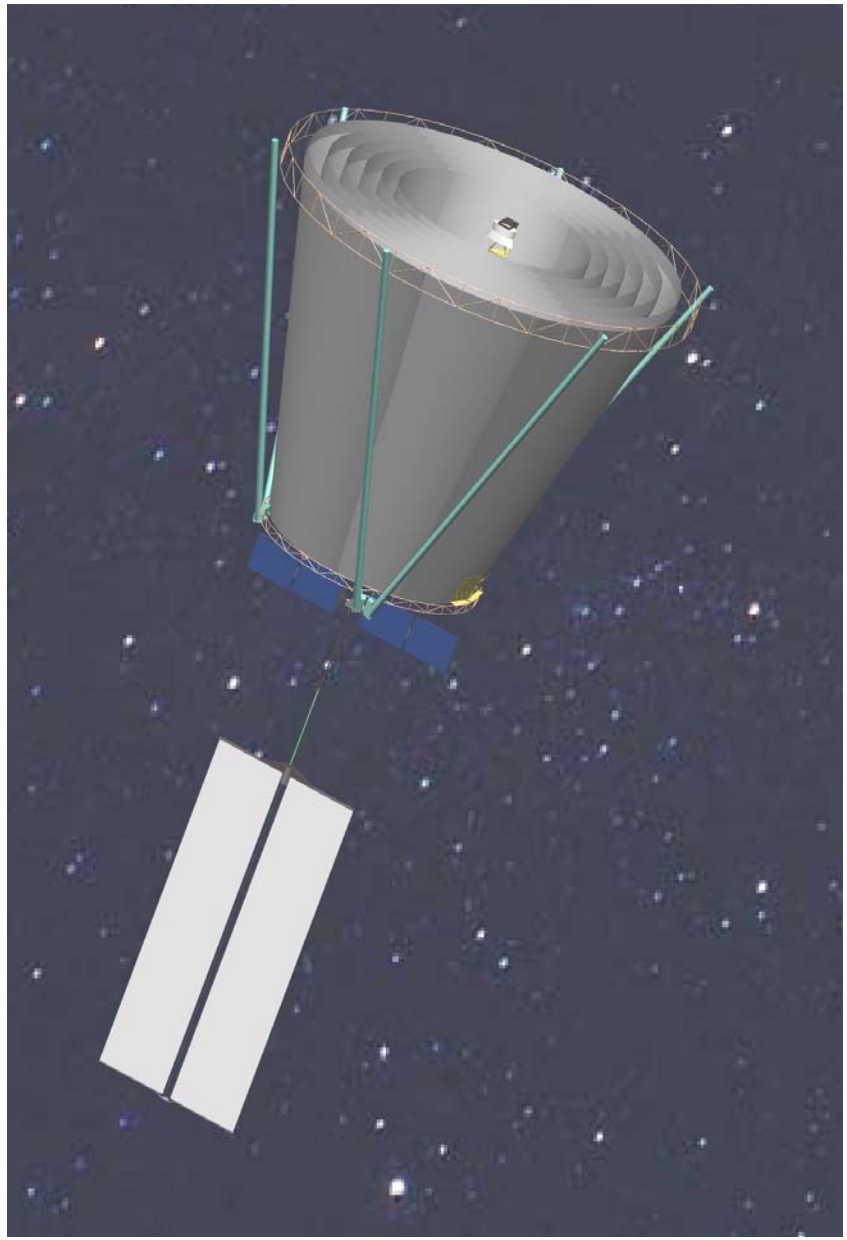
Optical Telescope Assembly

Thermal Sub-System

Louis Fantano

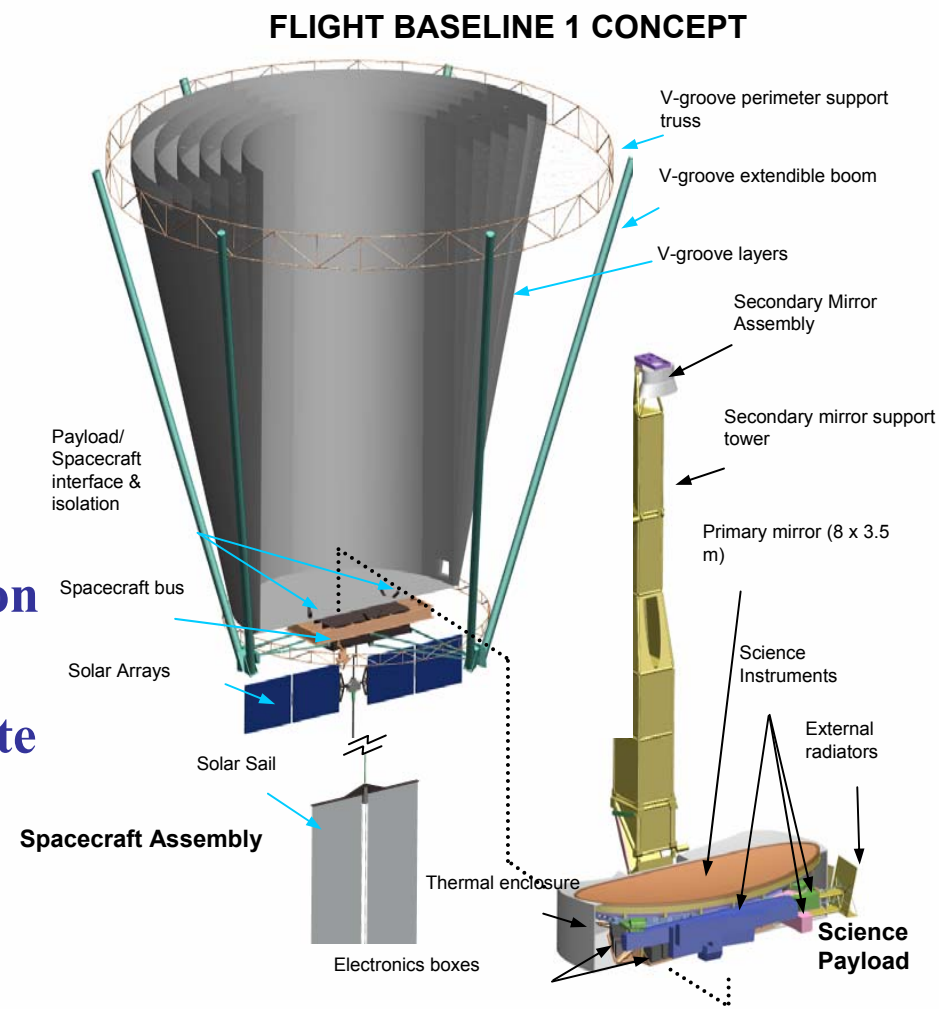
Contributors:
Cliff Jackson

11-12 July 2005

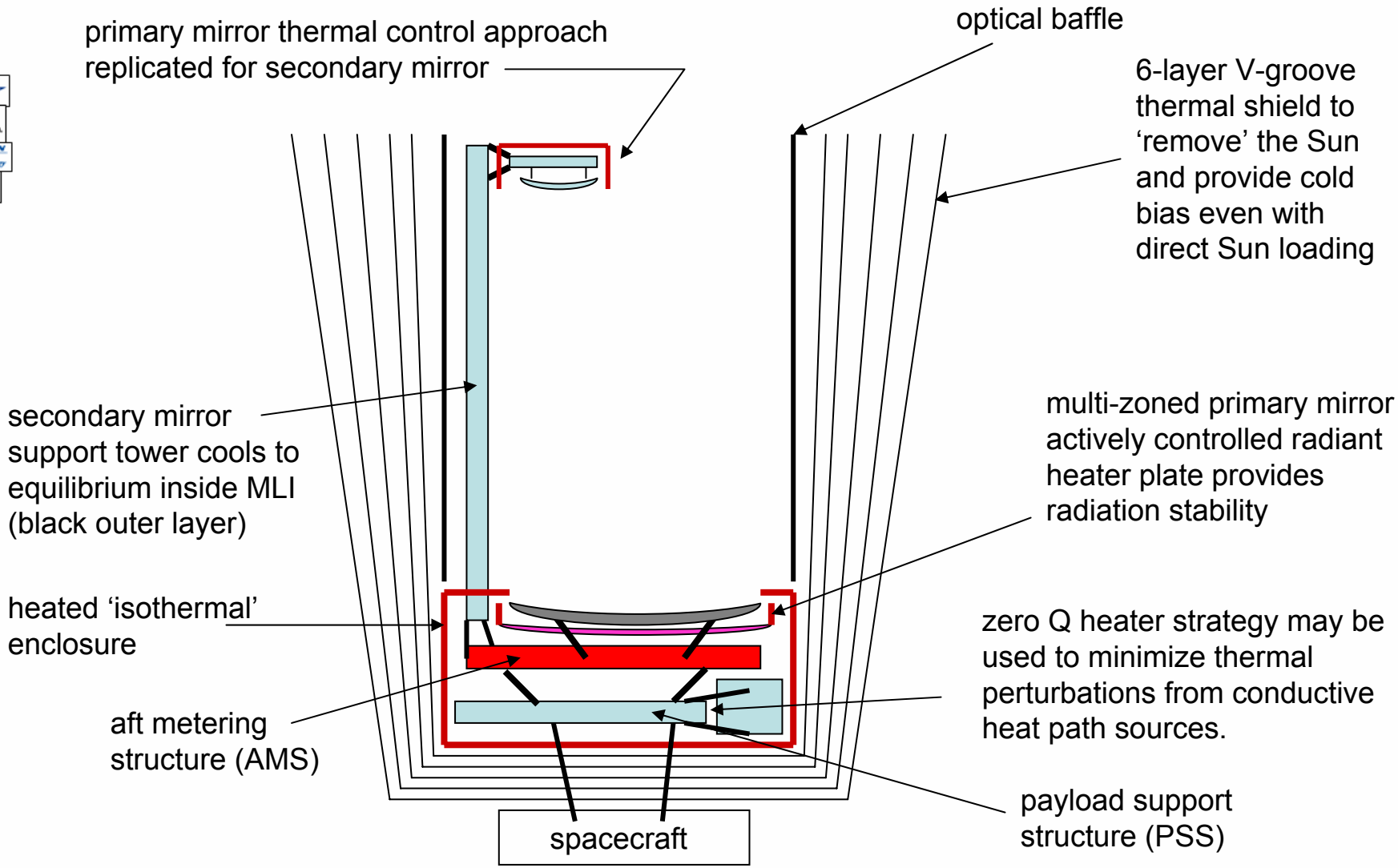


Presentation Outline

- Thermal Design Schematic
- Radiation Thermal Control Strategy
- Conduction Thermal Control Strategy
- Thermal Design Implementation
- OTA Dissipated Power Estimate
- OTA Thermal Sub-System Status

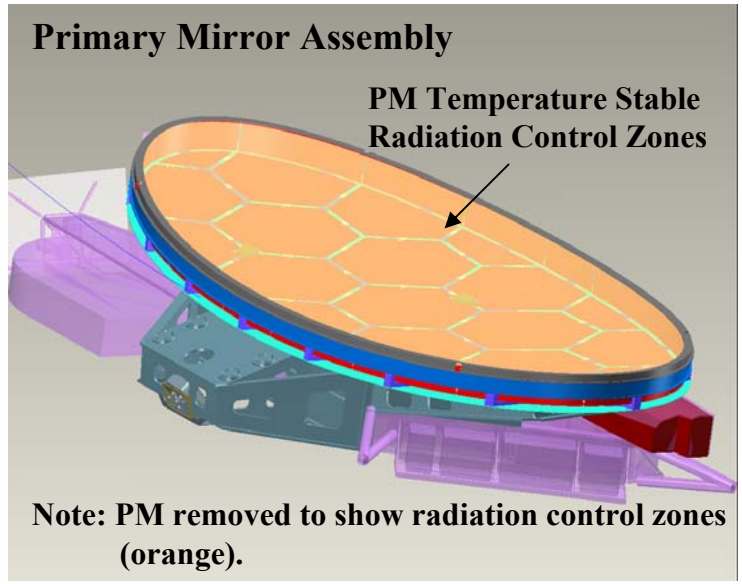


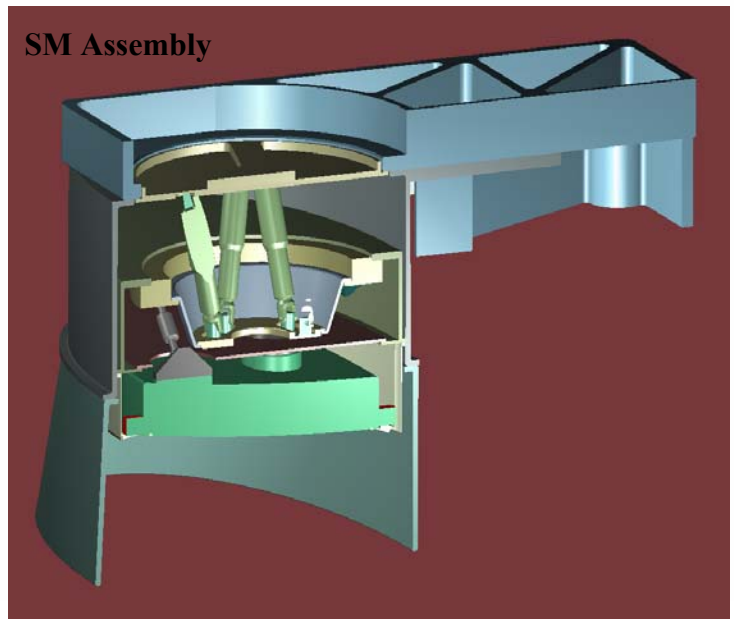
Thermal Design Schematic



Radiation Thermal Control Strategy

- OTA radiation thermal control is achieved via a combination of passive and active thermal control techniques.
  - Heaters and Temperature Sensors
  - Thermal Control Electronics
- The PMA and SMA are thermally controlled by forming a temperature-stable radiation environment around each element's perimeter and rear using K1100 composite panels as temperature control zones.
- All TPF-C OTA electronics boxes, with the exception of the LD5 boxes, are mounted to the JPL-provided Engineering Electronics Thermal Plate.



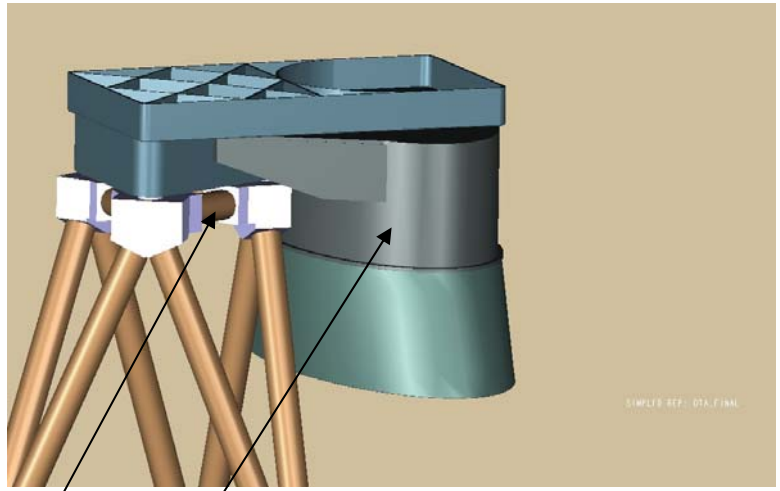


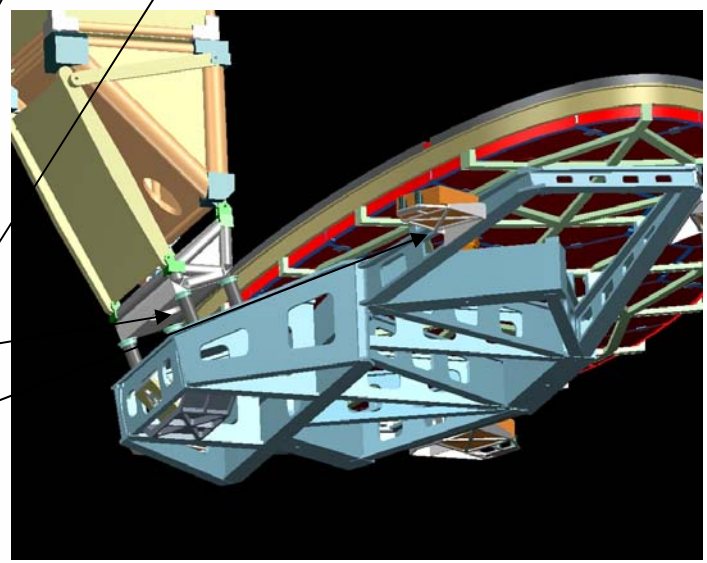
Conduction Thermal Control Strategy

Zero Q Conductive Interface Heater Strategy

- Goal – Achieve near zero heat flow at key conduction interfaces while minimizing power required to do so.

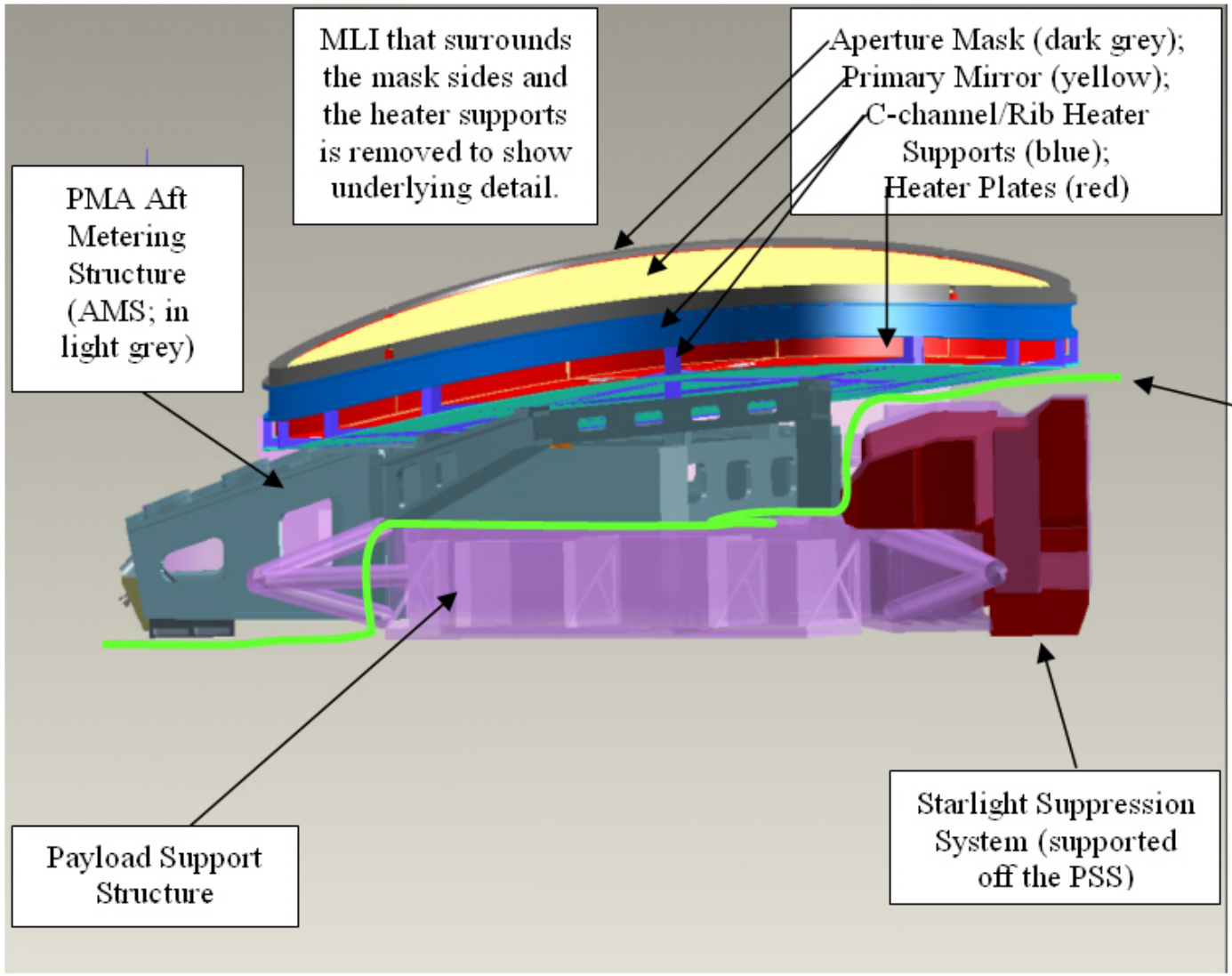
- All key conduction interfaces may employ a zero heat flow (Zero-Q) thermal control strategy to achieve temperature stability based on analyses results. The following are candidate conduction interfaces that might employ the Zero-Q heater strategy:
  - SMA / SST Isolation Struts
  - SMA-Bipod / Secondary Mirror
  - PMA / SST-Isolation-Struts
  - PMA-Bipod / Primary Mirror





Thermal Design Implementation

Primary Mirror Assembly (PMA)



Thermal Design Implementation

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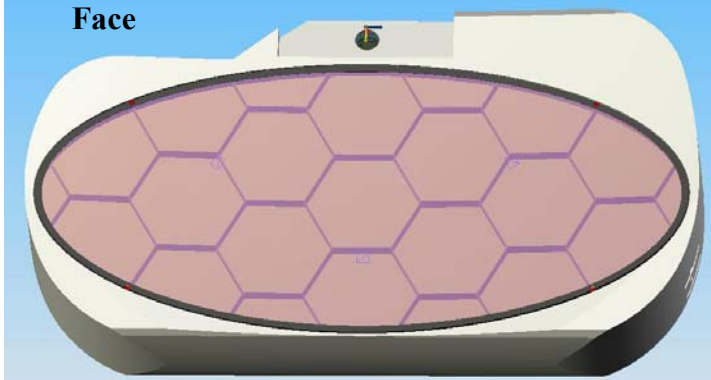
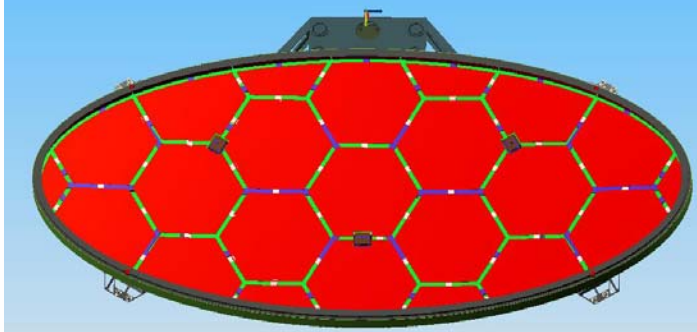
Top Down PMA View showing the Iso-Thermal Enclosure (IE; white). PM segments made visible through partially transparent PM Front Face



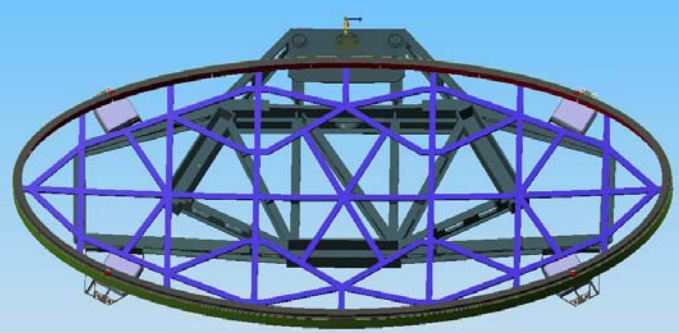
1

Same View with IE & PM removed. Note green MLI visible through gaps between rear thermal control heater zones (red).



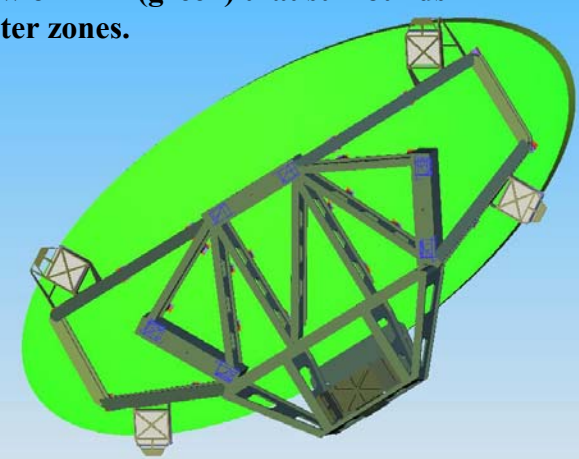
2

MLI, bipods, and aft PM heater zones removed. Note the four (4) LD5 boxes.



3

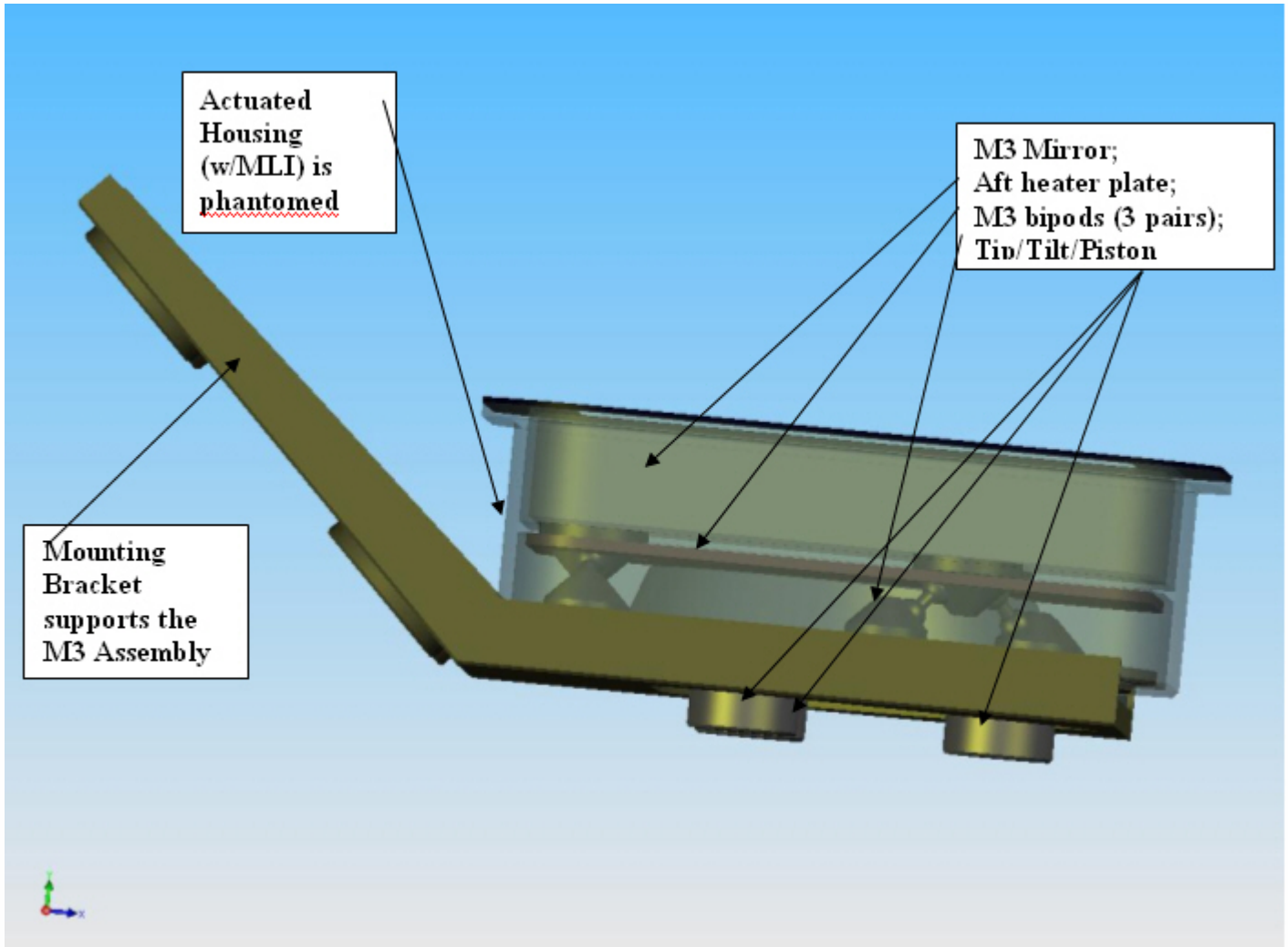
View of MLI (green) that surrounds PM heater zones.



4

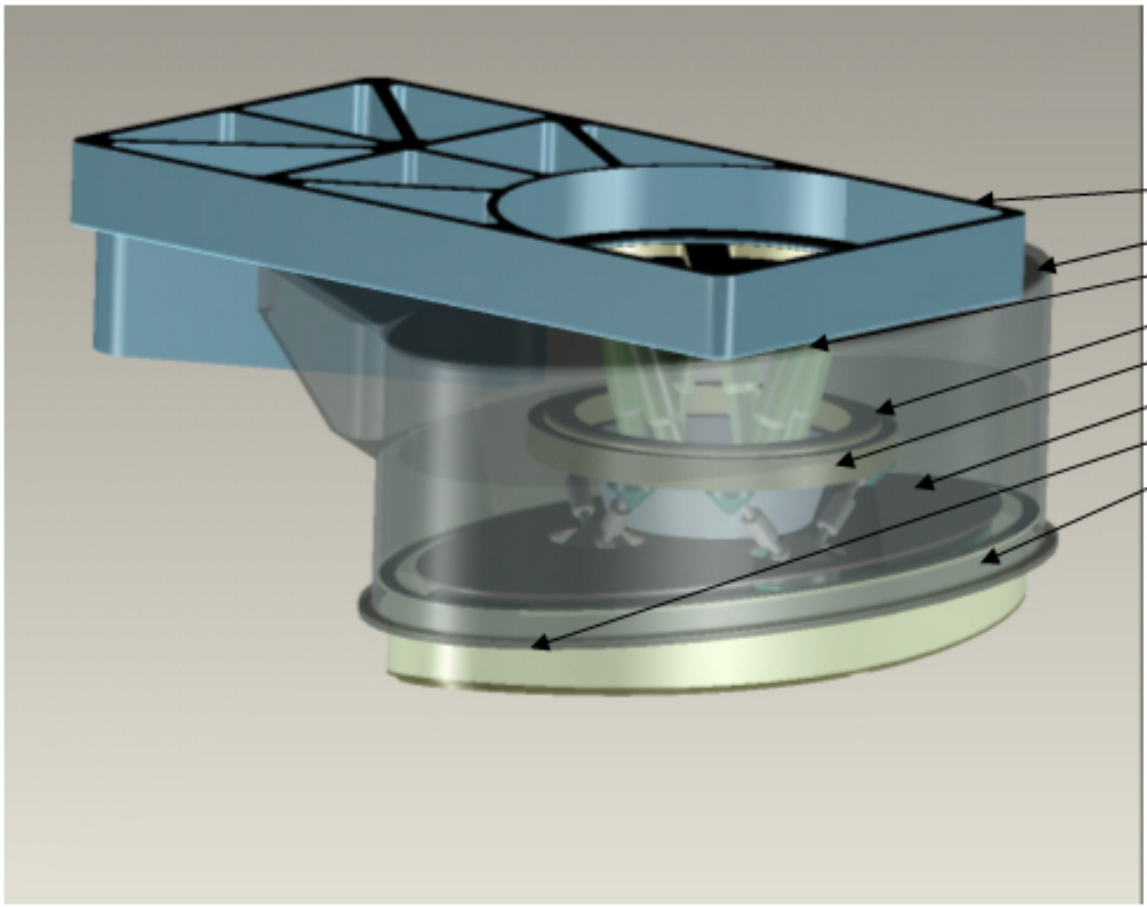
Thermal Design Implementation

M3 Fold Flat



Thermal Design Implementation

Secondary Mirror Assembly (SMA)



- Cantilever Bracket;
- Thermal Enclosure;
- Hexapods (6);
- Strong back
- SM Bipods (3 pairs);
- Aft Heater Plate;
- Aperture Mask;
- Peripheral Heater Plate;
- SM Baffle (not shown)

OTA Estimated Power Dissipation

	OTA Observing Mode Power Dissipation			
	#	Estimated Power	Total	Power Fluctuation
		W	W	Delta W / 8 Hrs
Electronic Boxes				
LD5 Laser Boxes	4	3	12	~ 0
TSCE Box	1	56	56	~ 0
MCE Box	1	20	20	Duty Cycle TBD
LME Box	1	6	6	~ 0
Other Components				
SMA Coarse Actuators	6	TBD	TBD	~ 0
SMA Fine Actuators	6	TBD	TBD	Duty Cycle TBD
M3 Actuators	3	TBD	TBD	~ 0
Total Component Power			**94**	
Heater Power		TBD	TBD	TBD

OTA Thermal Sub-System Status

- The proposed OTA thermal control system qualitatively provides an extremely stable thermal environment to TPF OTA optical elements.

- The quantitative thermal performance associated with the proposed design is being modeled and preliminary thermal performance results are encouraging.

Integration, Test, and Verification Plans

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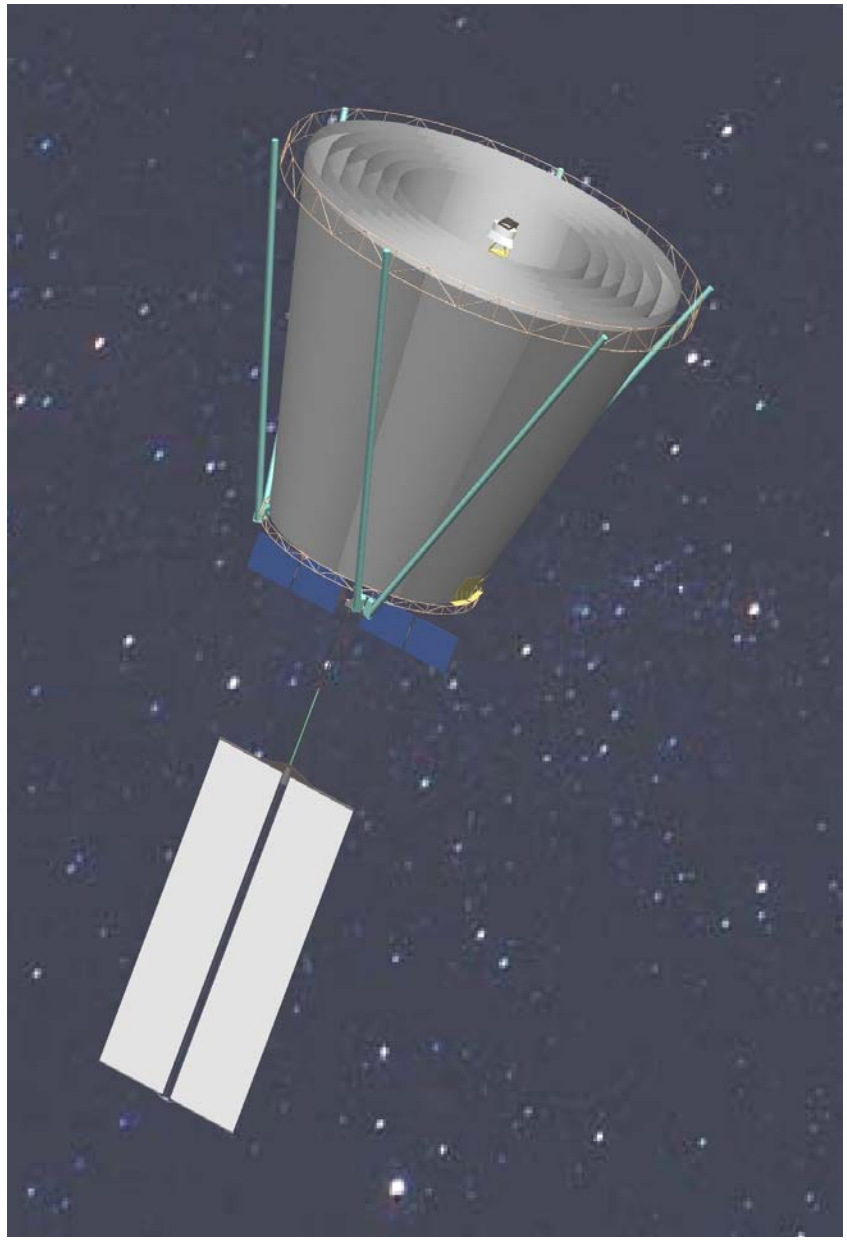
Andrew Smith
Michael Krim
Joe Pitman

11-12 July 2005

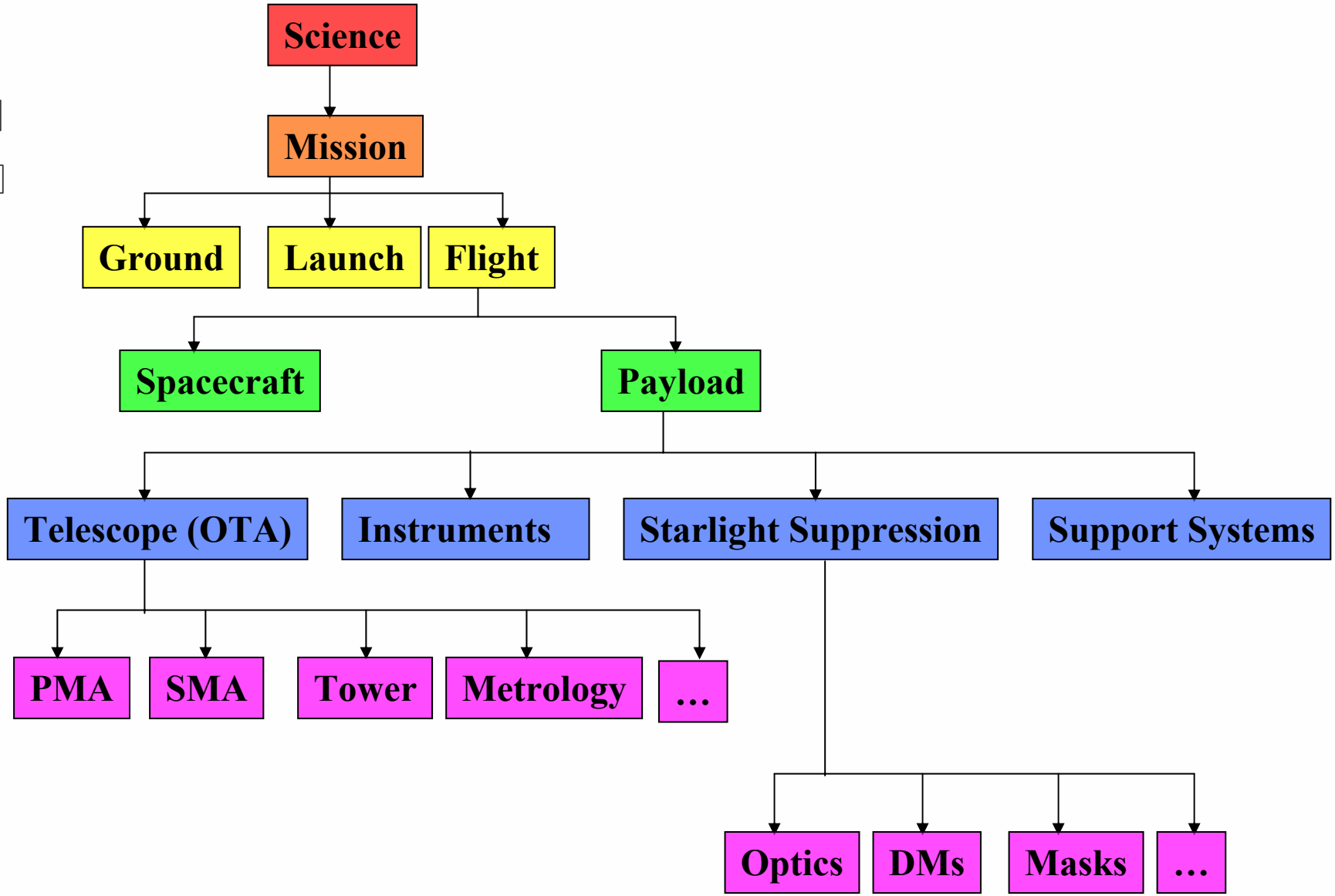


Outline

- Requirements Levels
- Verification Matrix example
- Verification overview: telescope assembly
- Primary mirror verification and test
- Overall integration and test flow
- Future Work

- Backup charts: more detailed I&T flows

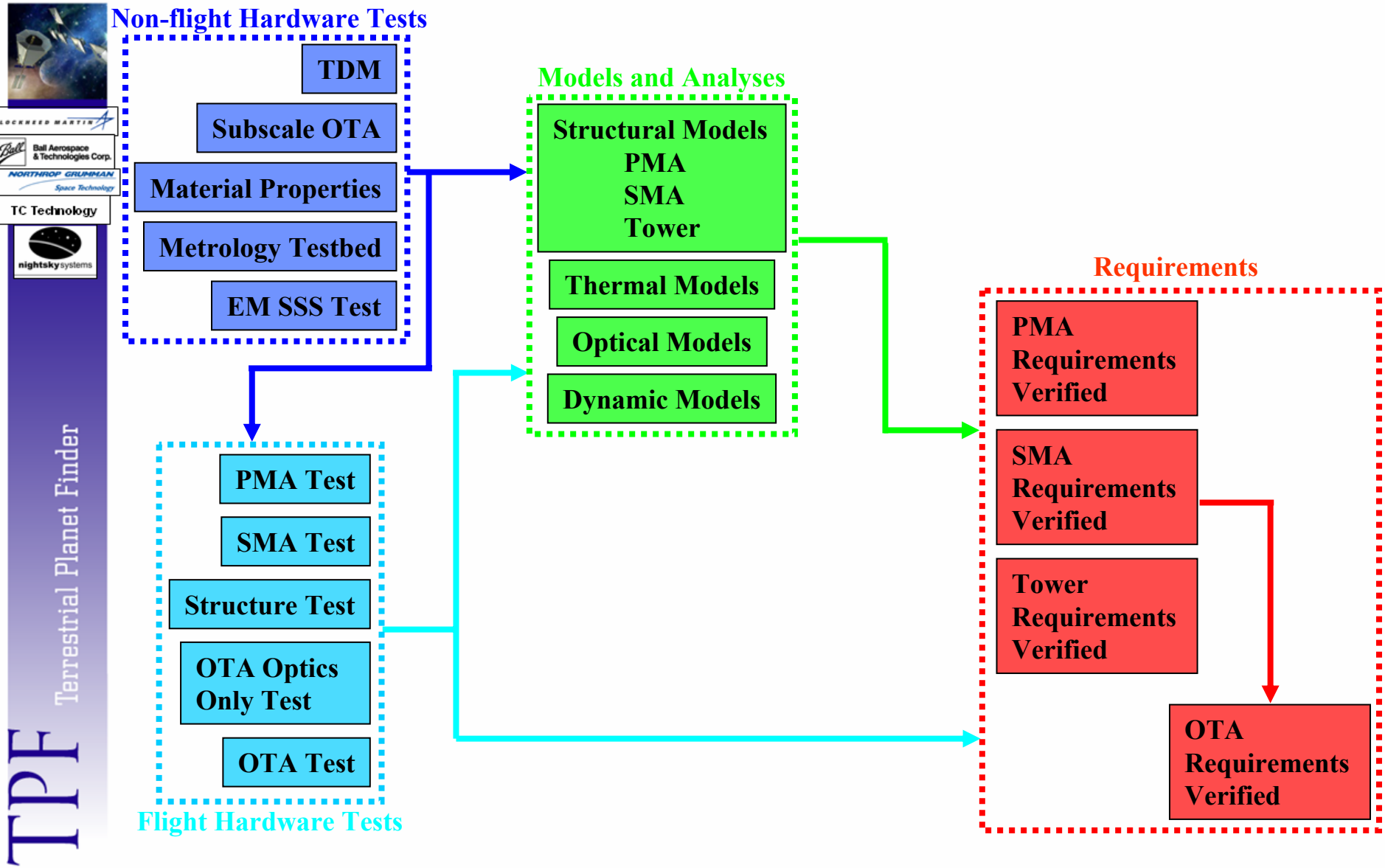
Requirement Levels



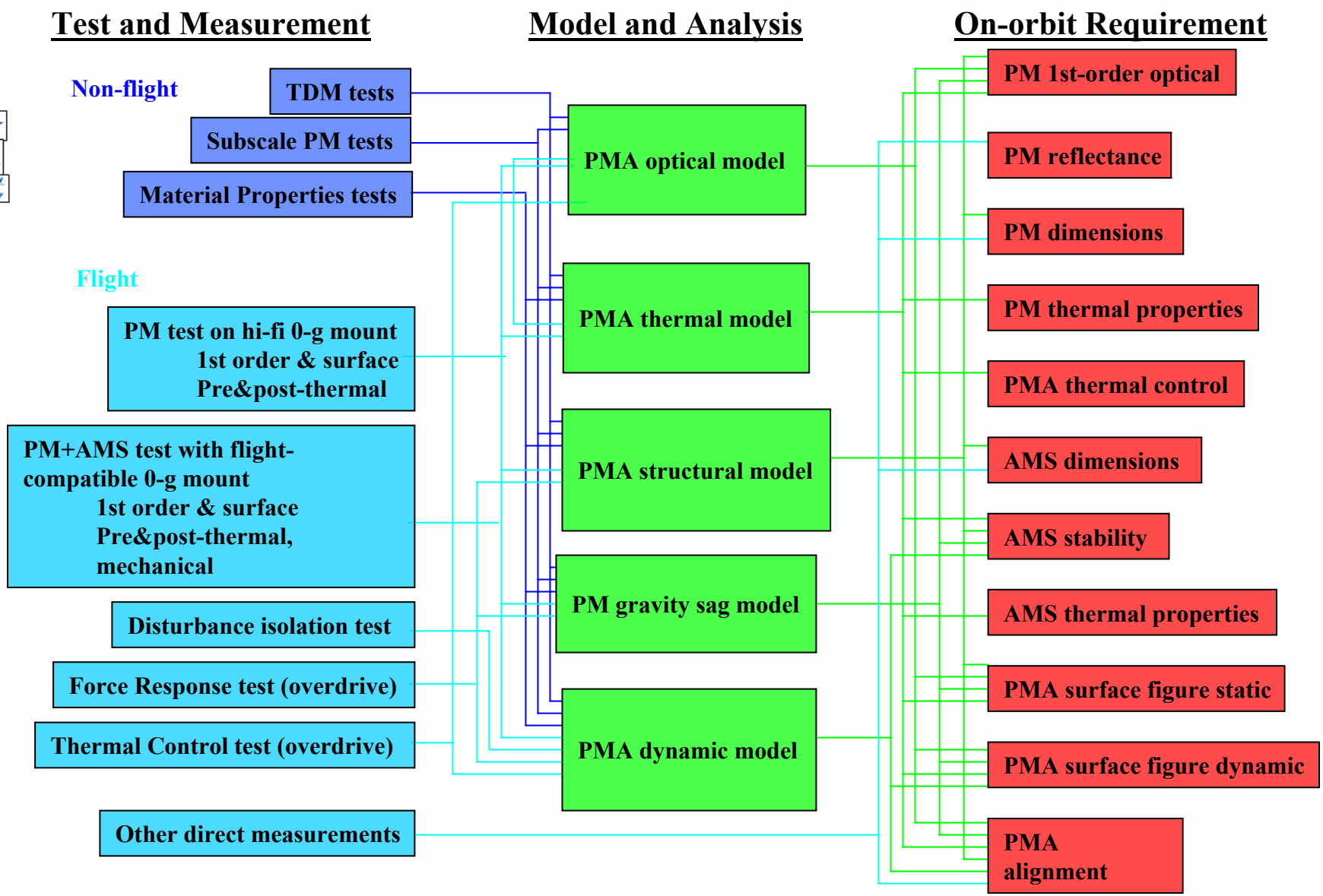
Verification Matrix (section)

REQUIREMENTS	TEST	ANALYSIS		COMMENTS
3.3.1 OTA				
3.3.1.1 OTA level requirements				
3.3.1.1.1 *First order optical properti*				
3.3.1.1.1.1 Magnification	x			
3.3.1.1.1.2 Field of view	x			
3.3.1.1.1.3 Effective focal length	x			
3.3.1.1.1.4 Focal ratios	x			
3.3.1.1.1.5 Focus location	x			
3.3.1.1.2 *Resolution*				
3.3.1.1.2.1 Major axis		x		Based on full-aperture measurements of idividual elements and subaperture end-to-end measurements.
3.3.1.1.2.2 Minor axis		x		Based on full-aperture measurements of idividual elements and subaperture end-to-end measurements.
3.3.1.1.3 *Wavefront*				
3.3.1.1.3.1 Dynamic		x		Combines sub-aperture ene-to-end measurements made in an environment that comes as close as possible to predicted flight mechanical and thermal disturbances with CTE and disturbance response measurements of individual elements, subscale OTA testbed measur
3.3.1.1.3.2 Static		x		Combines multiple sub-aperture end-to-end measurements. Compare with verified model.
3.3.1.1.4 *Contrast contribution*		x		Based on measurements with GSE coronagraph and HCIT results.
3.3.1.1.5 *Pointing*	x			Verification of secondary mirror contribution to pointing control
3.3.1.2 Primary mirror assembly				
3.3.1.2.1 *PMA level requirements*				
3.3.1.2.1.1 Surface figure				
3.3.1.2.1.1.1 static		x		Center-of-curvature measurement of PM surface figure using gravity off-loading support and model of residual figure error.
3.3.1.2.1.1.2 dynamic		x		Combines surface figure measurements made under over-driven thermal and mechanical loading conditions with measurements of subscale PMA response to flight-like environmental loading.
3.3.1.2.1.2 Alignment	x			Alignment with metering structure.
3.3.1.2.2 *Primary mirror*				
3.3.1.2.2.1 First order optical pro	x			
3.3.1.2.2.2 Mechanical Properties				
3.3.1.2.2.2.1 Mass	x			
3.3.1.2.2.2.2 Dimensions	x			
3.3.1.2.2.3 Reflectance	x			
3.3.1.2.2.4 Thermal properties				
3.3.1.2.2.4.1 CTE distribution		x		Based on measured surface figure response to applied thermal perturbations. Compare to direct measurements of samples from ULE

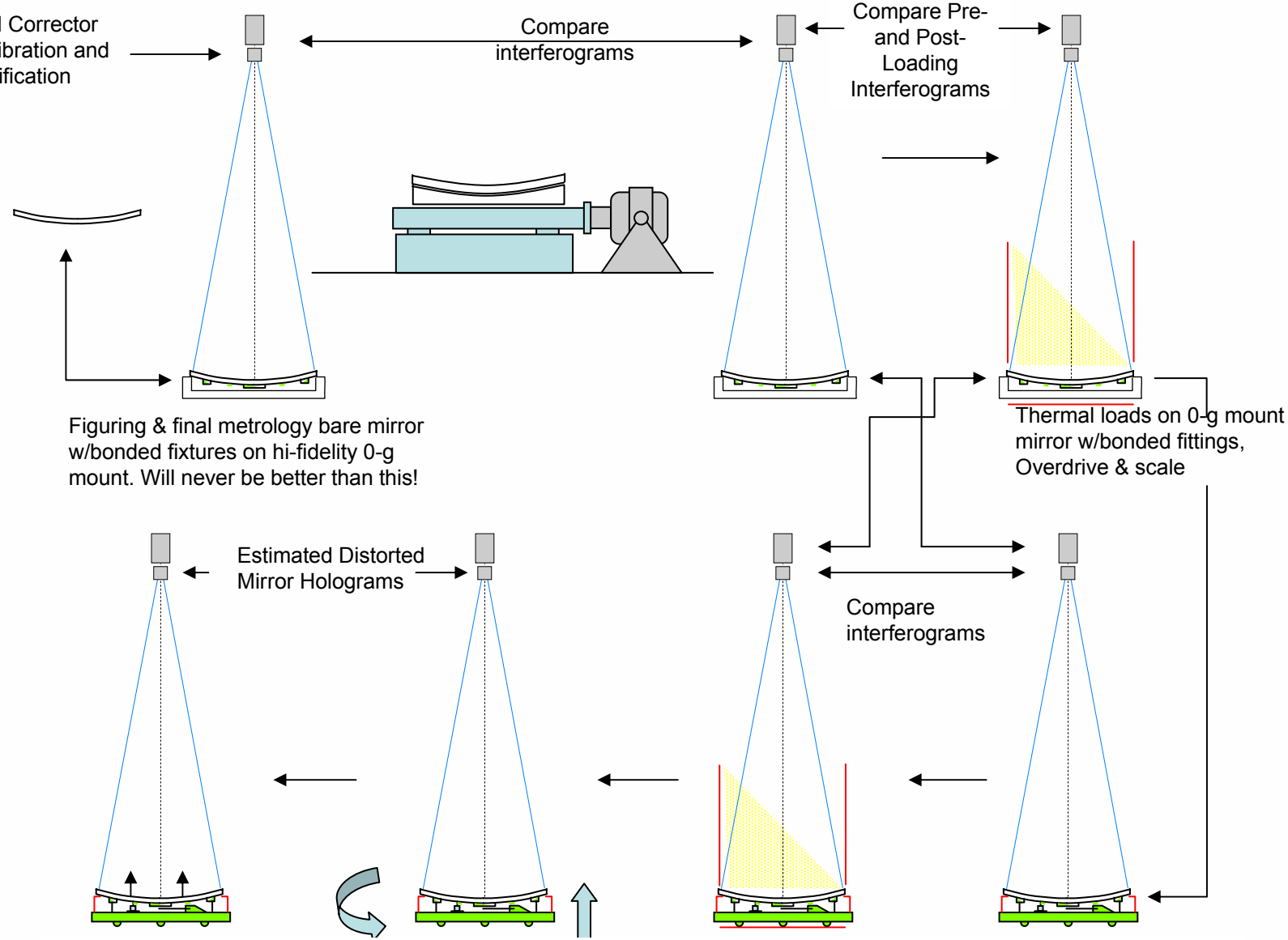
Verification Overview: OTA



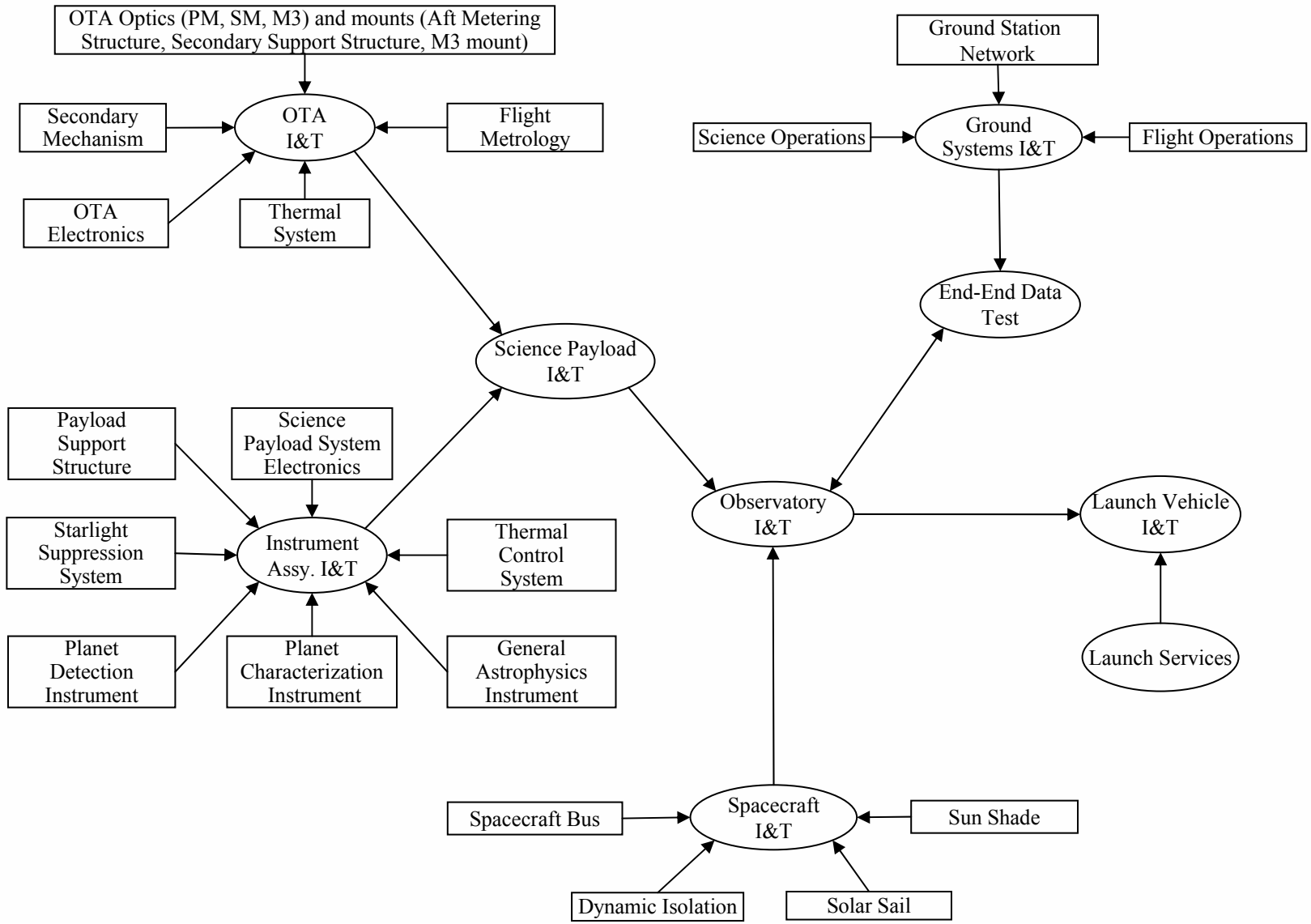
Verification Example: Primary Mirror Assembly



Test Flow Example: Primary Mirror Assembly



I&T Flow Overview

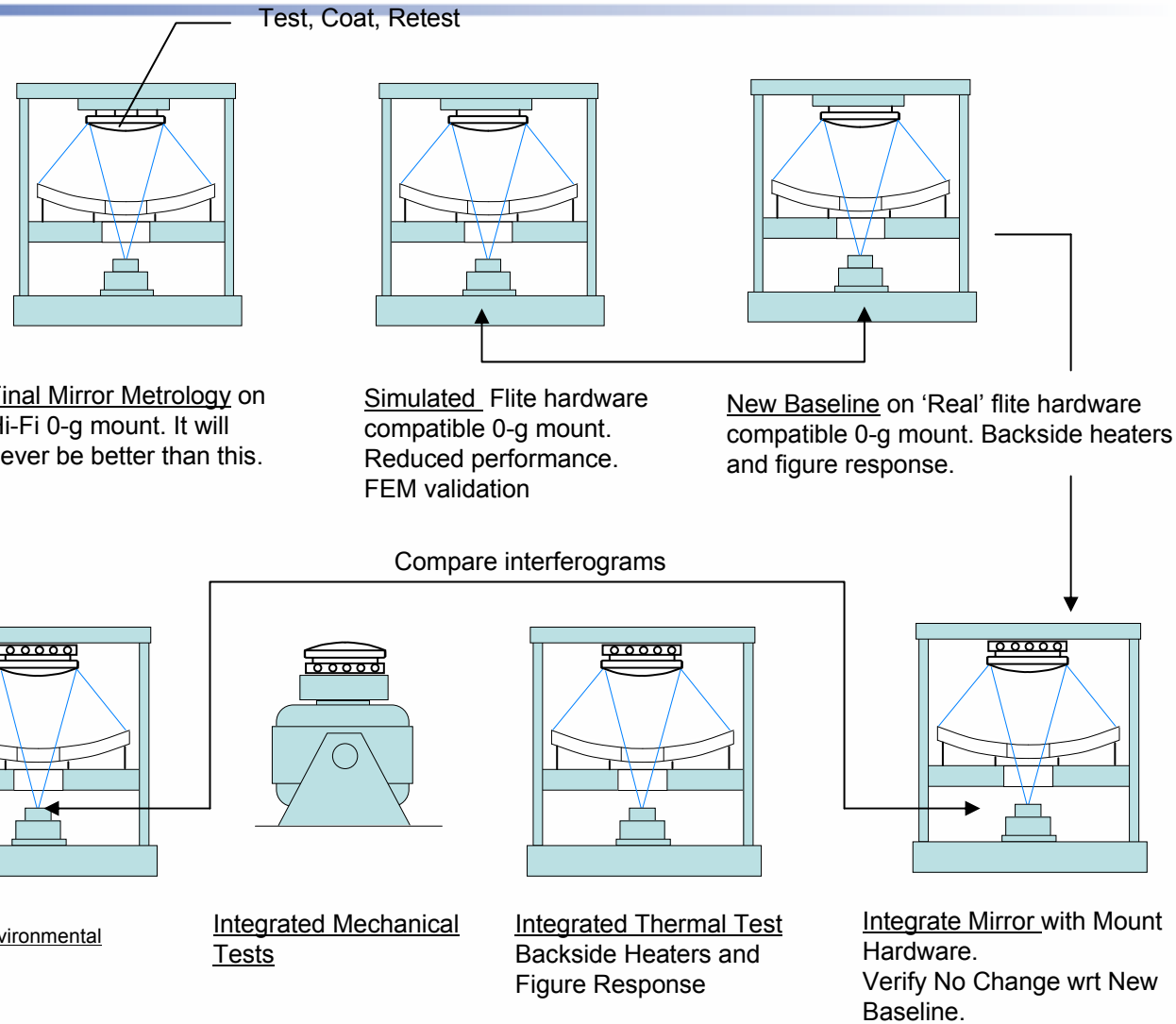


Future Work

- Complete requirements definition and fill in verification matrix.
- Trade verification by analysis against test to rely on test as much as is feasible.
- Develop more detailed plans for the test and analysis programs.
- Detailed I&T planning to date has concentrated on the Optical Telescope Assembly. Planning will be extended to include the entire payload, the flight segment and the mission.

Backup Charts

Matching, Verifying and Integrating the SMA



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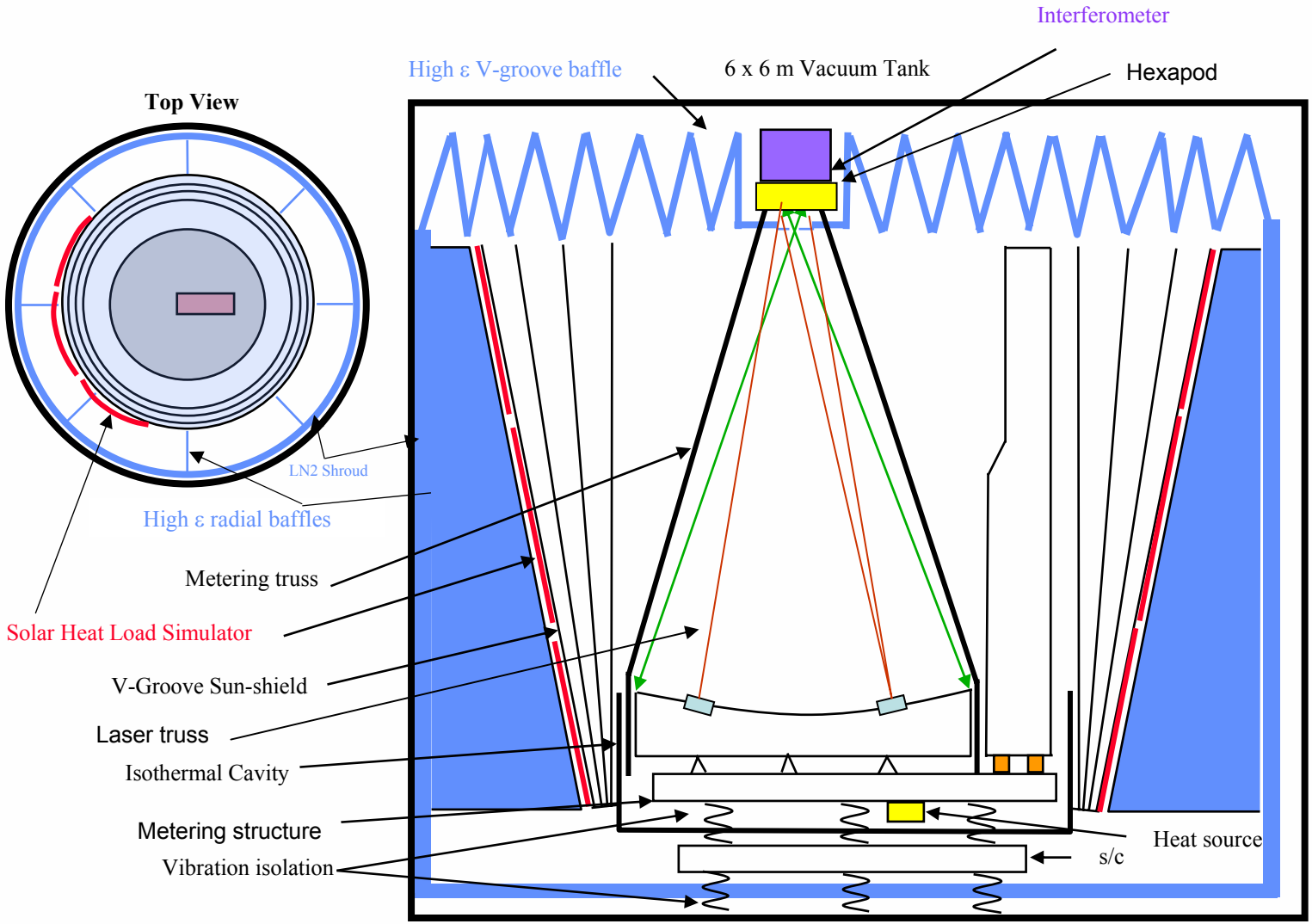
Primary Mirror Thermal Control

Flight level control demonstrated at sub-scale level

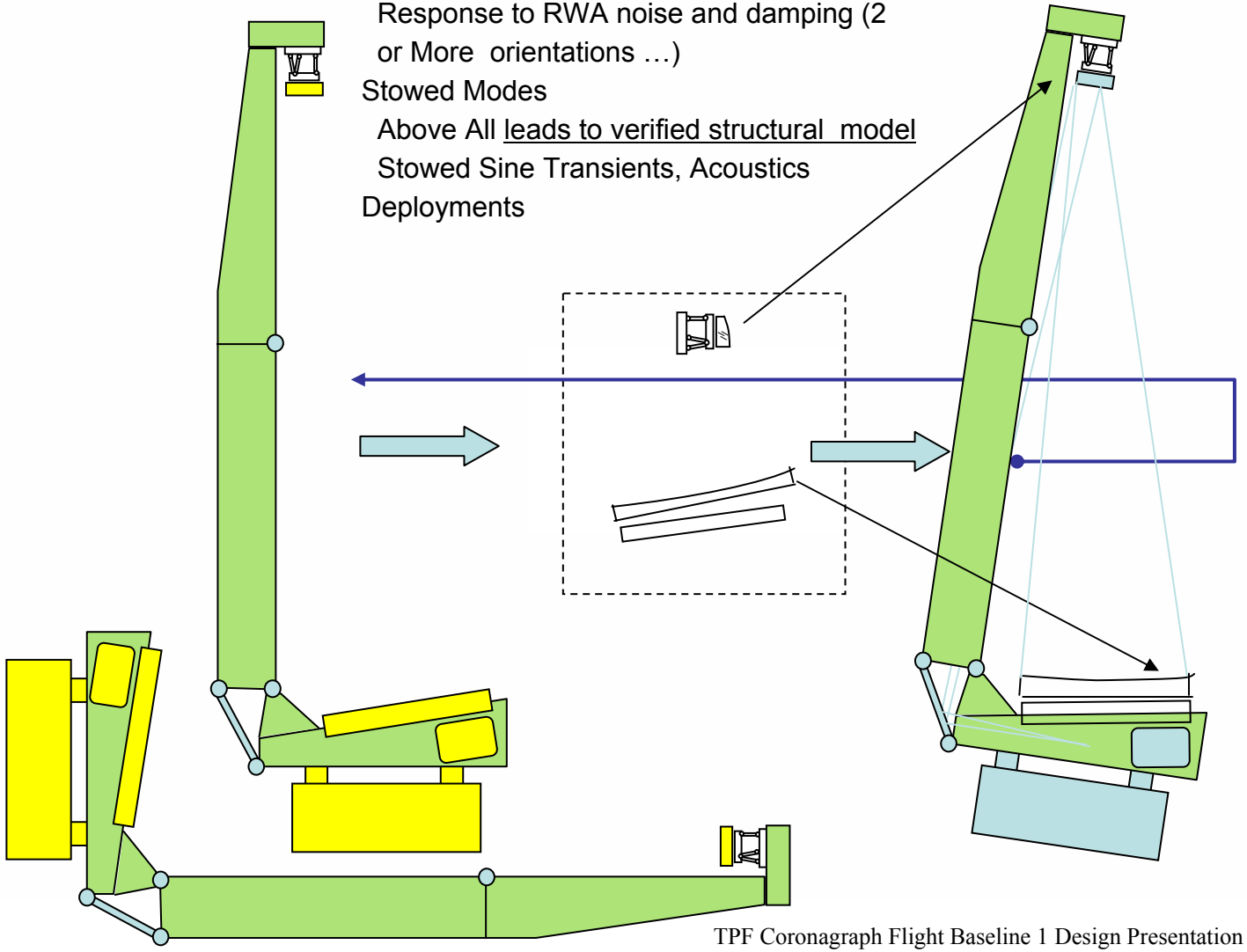


Structural Tests and Optical Component Integration

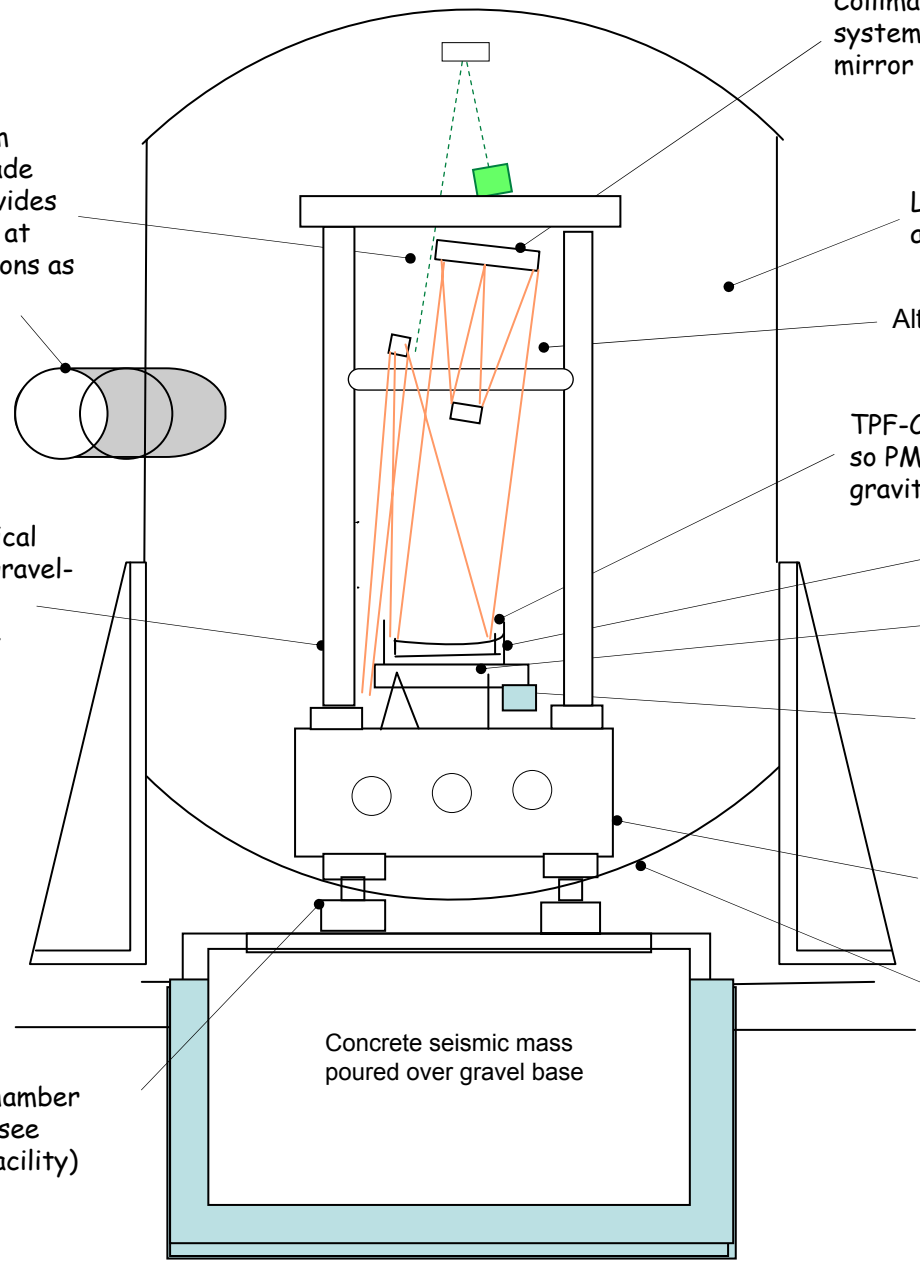
Deployed Modes (in 2 or More Orientations to discern any gravity dependence)
- Response to RWA noise and damping (2 or More orientations …)

Stowed Modes
- Above All leads to verified structural model
- Stowed Sine Transients, Acoustics

Deployments



A Candidate Hardware Visualization



Collimator mounted on track system for translation along mirror long axis direction

3.6m COLLIMATOR or 3.6m FLAT… Collimator v. Flat trade discussed in Memo ____. Provides partial aperture illumination at one of several (three) locations as shown below.

LN2 cold wall and IR heater arrays not shown

Alternative A/C Flat

TPF-C optical components tilted so PM is horizontal to facilitate gravity off-loading

Tower structure uses cylindrical members…can be filled with gravel-like plastic damping material. Cross-bracing not shown here

Heater/TCS

Abbreviated Off-Loaders

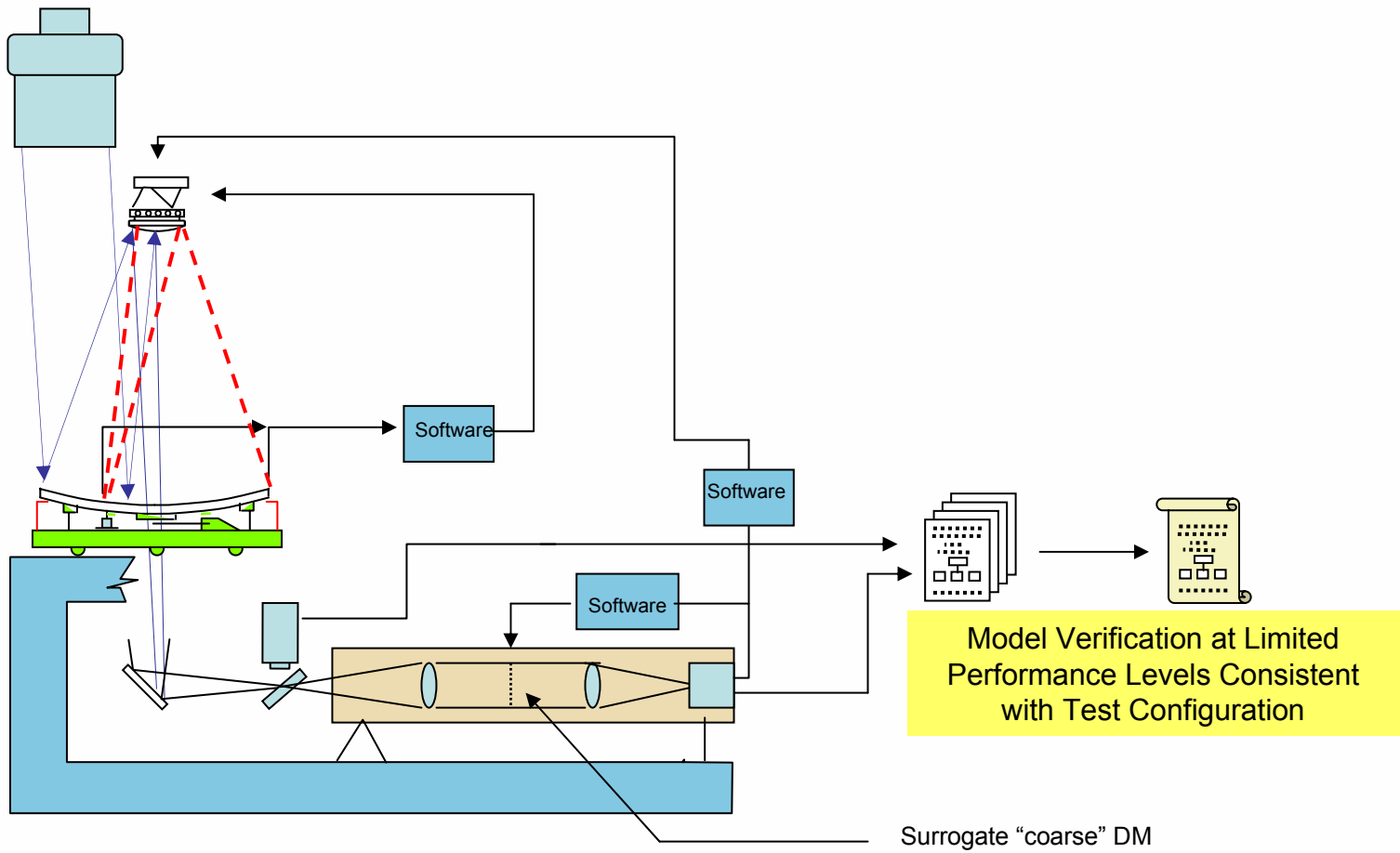
Starlight supression system and Data Camera

Isolated 'Master Support' Platform…about 5E-12 g^2/Hz (to be checked !)

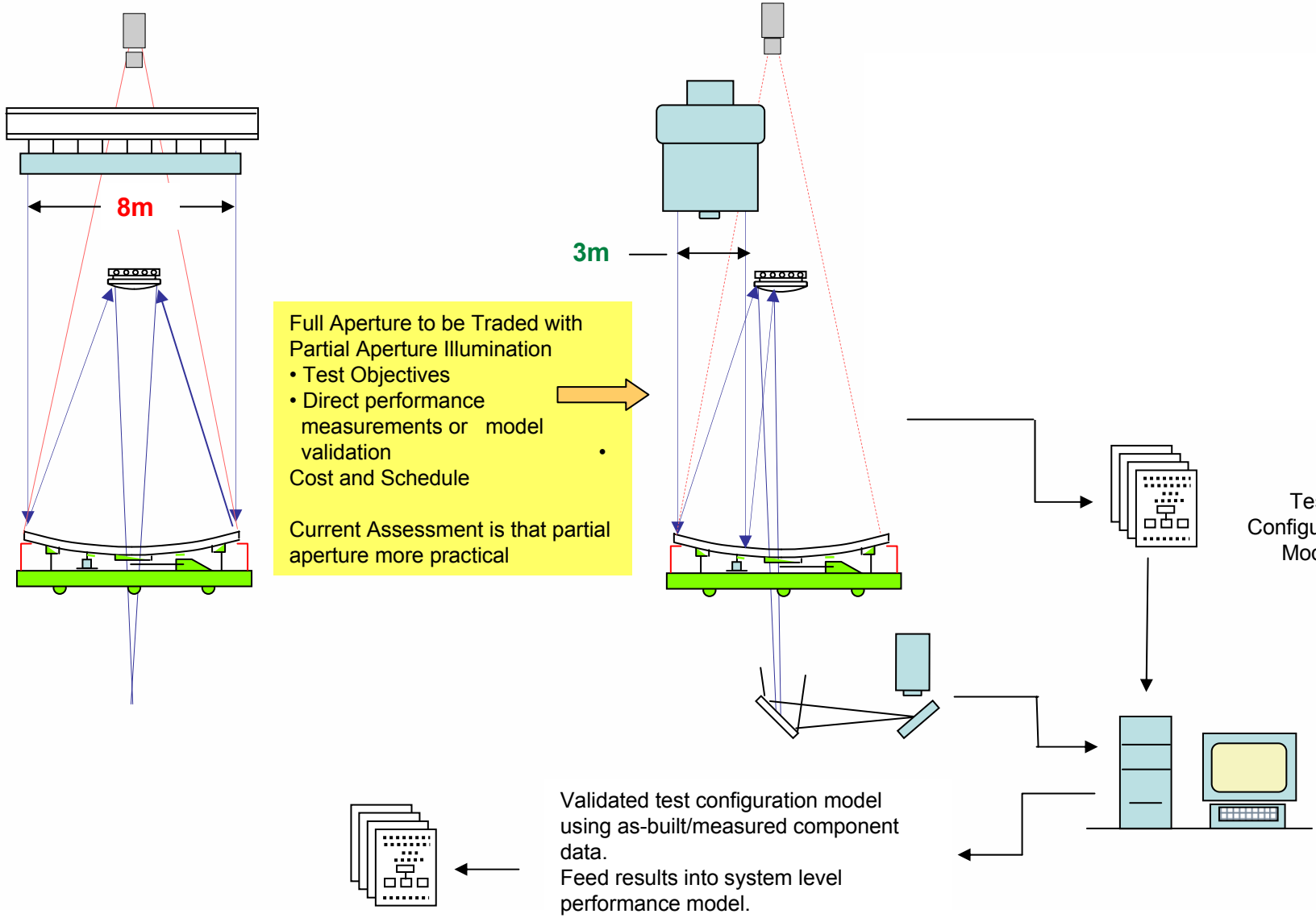
Vacuum Chamber attached to building floor, NOT to optical tower structure

Pneumatic Isolators …penetrates vacuum chamber through bellows seals (see Danbury Chamber 'A' facility)

OTA-to-Coronagraph Interface Verification



OTA Optics-Only Verification
Matched PM/SM Using Verifiable Test Equipment



Full Aperture to be Traded with Partial Aperture Illumination
- Test Objectives
- Direct performance measurements or model validation
- Cost and Schedule

Current Assessment is that partial aperture more practical

Validated test configuration model using as-built/measured component data.
Feed results into system level performance model.

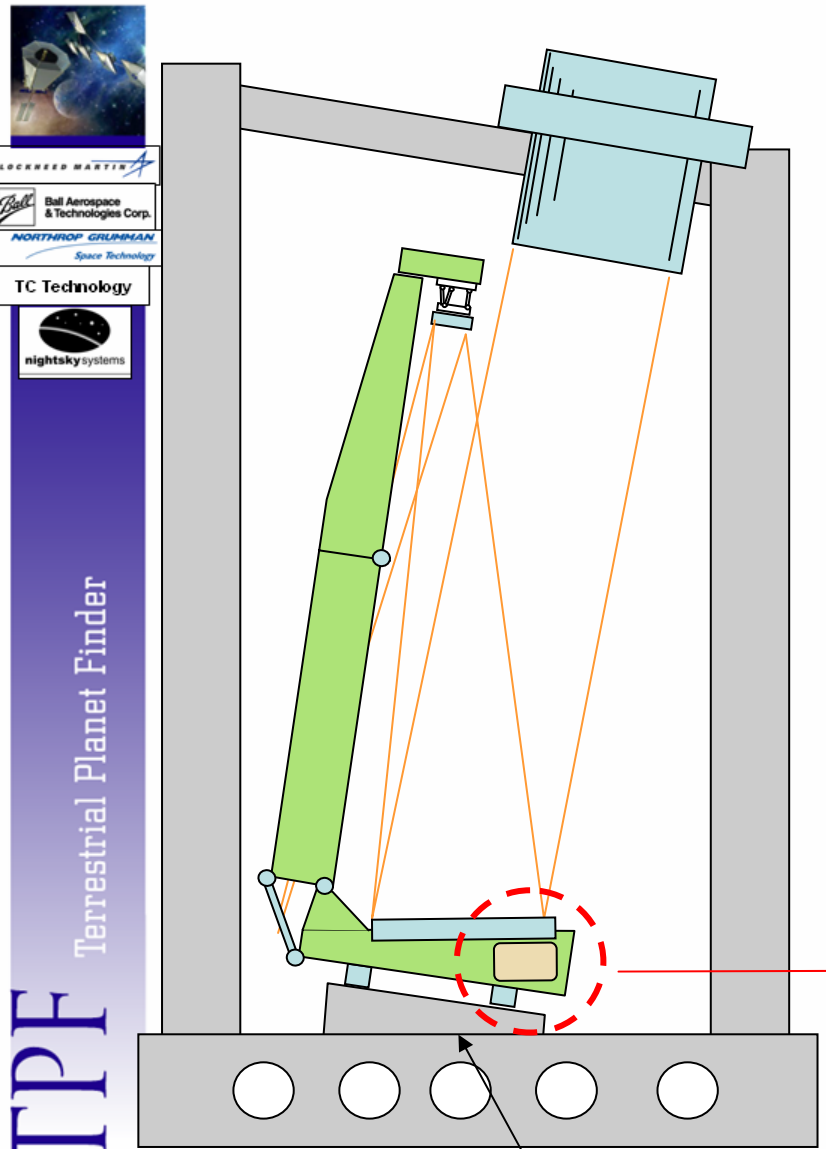
OTA-to-Coronagraph Interface Verification

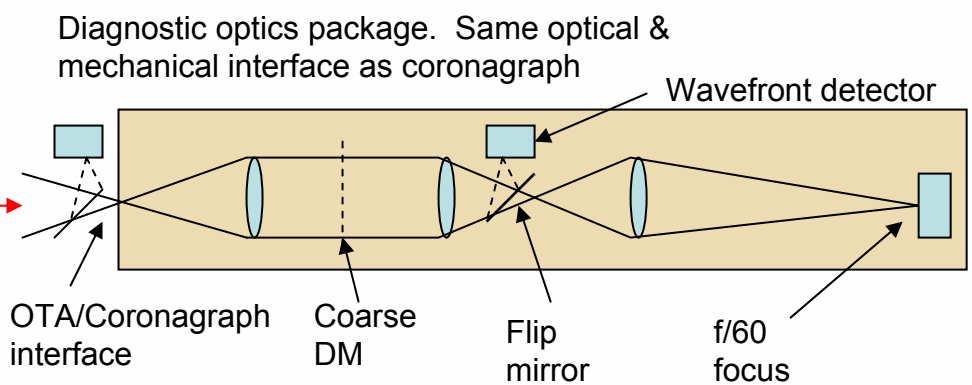
OTA level Requirements

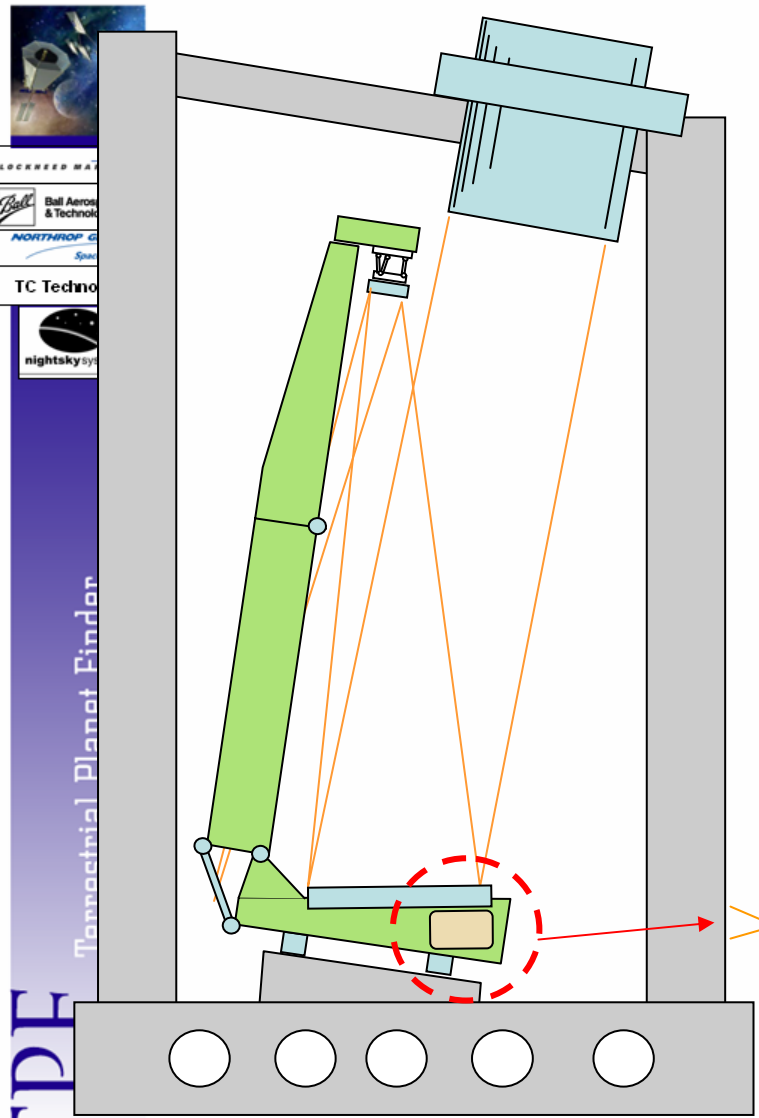
Measure in completed telescope & correlate with model
-effective focal length
-field of view
-back focus
-static wavefront quality

Measure SMA response to ±5mas simulated pointing fluctuation at f/60 focus. (Linear motion = ±5 µm and 12µm along orthogonal axes.)

Assumptions:
1. Optical measurements made at room temperature in vacuum.
2. Only thermal balance tests are made at LN2 temperatures. (Collimator removed.)







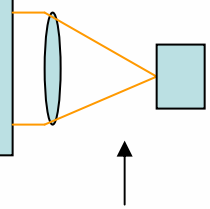
Suggested OTA – Coronagraph System Test.

The OTA is mated with a high fidelity copy of the front end optics of the cornagraph. (Front-end optics include all optics up to the deformable mirrors.) A test is made to establish that the wavefront at the entrance pupil of the Star Supression System (SSS) will be within the capture range of the deformable mirrors and that the pupil image will be located correctly on the deformable mirrors. If these goals are achieved then it can be inferred that the combined OTA/coronagraph will provide the required contrast when the flight coronagraph is mated to the OTA..

Assumptions:

1. The flight front-end optics will relay the light in the OTA image properly to the SSS.
2. Given that the wavefront presented to the SSS is within the capture range of the deformable mirrors the SSS will produce the required contrast.

Copy of front-end coronagraph optics. Includes fold mirrors, collimators, anamorphic optics & relay optics. Duplicates with high fidelity mechanical and optical interface with OTA & Star Supression System.



Wavefront detector

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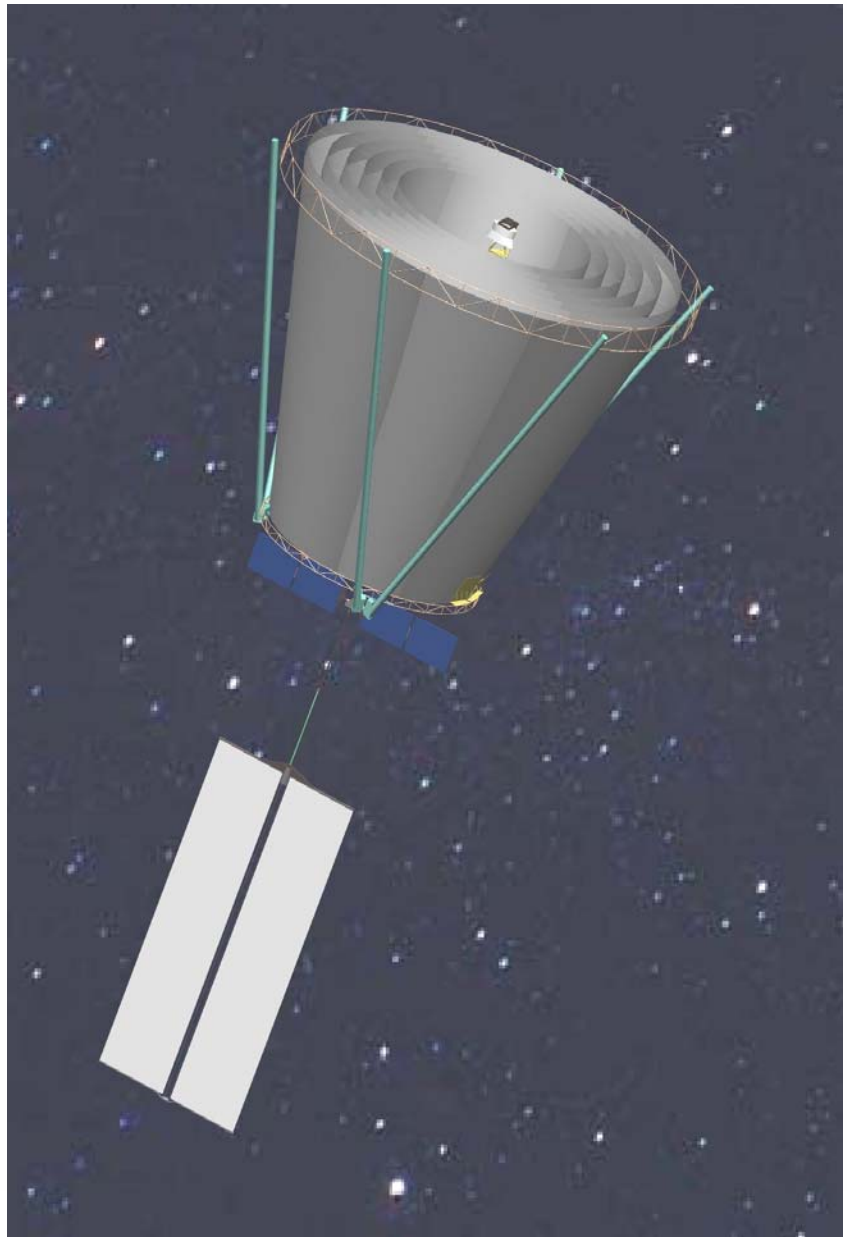
Modeling Introduction & Plans

Marie Levine

Contributors:
Modeling Team

11-12 July 2005



Content

- Iterative Design/Analysis Cycle Process
- Modeling Approach & Philosophy
- Cycle1 Analysis Goals, Products & Schedule
- Cycle1 Baseline Design for Core analyses
- Preliminary Tasks
- Current Status

(see backup slides for details of the modeling plan)

Design & Analysis Cycles through Project Phases: Not a linear process

PDR-CDR

Pre-Phase A → Phase B-C → Phase D

Explore Design Options
Trade-off Requirements
Optimize Performance
Identify Technology

Detailed Design Completed
Requirements Defined
Verification & Validation Planned
Technology Demonstrated

Flight Models Validated
As-Built System Verified

Increasing model fidelity & complexity

Iterative Design/Analysis Cycle Process

Cycle "n" → Cycle "n + 1"

Design Evolution
- Alternate Concepts
- Trade Study Results

Changing Conditions
- Emerging Requirements
- Reprioritized Goals
- New Constraints

4/1/05

Design Freeze
- Systems Eng'rg
- Baseline Design
- CAD model

5/6/05

Analysis Plan
- Results Goals
- Case Priorities

10/07/05

Design Refinement Decisions
- Updated Baseline Design
- Updated Req's for Cycle n+1
- Consolidated Alternate Design(s)

5/6/05

Model Creation
- Optical
- Structural FEMs
- Thermal
- Dynamics

Integrated Analyses
- Nominal Design & Conditions

Sensitivity Analyses & Design Perturbations

7/12/05

Prelim Analysis Results
- Review
- Plan Assessment

Legend

Cycle 1 Target Dates

Start — Done

Modeling path →

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Preliminary Tasks: "Cycle 0"

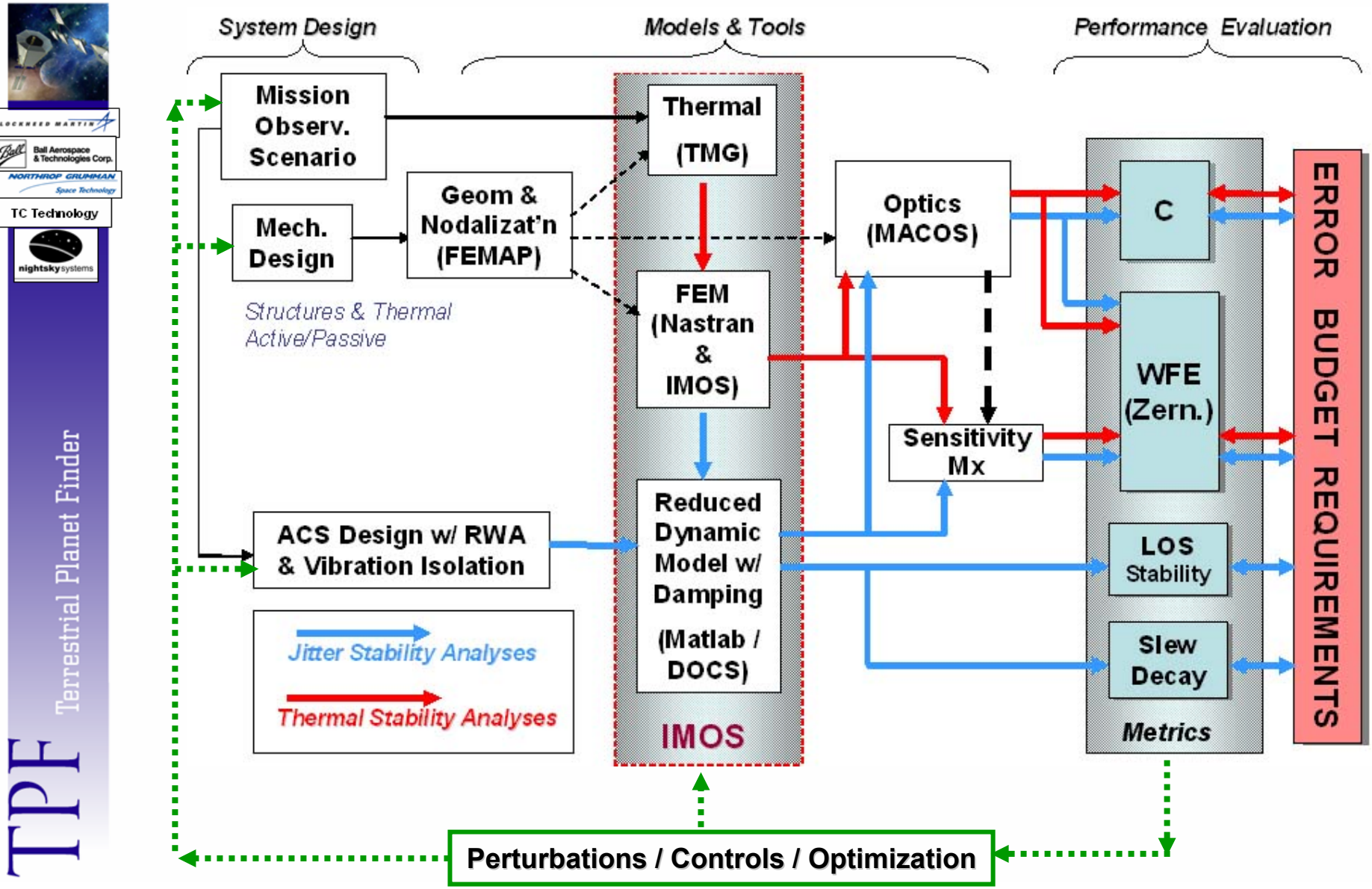
- Multi-center team coordination & communications:
  - New team starting this year, w/ some position changes
    - Get new team members up to speed about TPFC
    - Introduce and enforce modeling philosophy
  - Learning how to work together effectively
    - Establish modeling plans across disciplines & centers
      - Management coordination & progress tracking
    - Agree on modeling tools (esp. CAD & thermal)
      - Develop model transfer protocol
    - Establish communications
      - Across the country at many locations
      - Define meetings & attendance
      - Learn to use videoconferencing
- Modeling tool validation
  - Thermal (TMG): issues with limits of code accuracy, model size, …
  - Optical (MACOS): code de-bugging, diffraction propagation, …

Modeling Approach & Philosophy:
One Design / One Model / One Mesh

- **Design/Analysis configuration control & management**
  - Models represent frozen design & no changes permitted during analysis cycle (as tempting as it may seem)
  - Exercise model thoroughly to understand improvements for next cycle
  - Design configuration managed through common file depository on TPF library w/ enforced documentation & nomenclature

- **One Model / One Mesh**
  - Same model geometry & mesh for all <u>integrated systems</u> analyses and disciplines ("***mid-fidelity model***")
  - Single discipline models may require ***high-fidelity models*** (e.g., PM launch stress), but remains a super-set of the mid-fidelity model
  - Trades analyses conducted separately on ***low-fidelity models*** for quick assessment
  - Optical design model forms basis for CAD/Thermal/Structural models
  - Same mesh reduces modeling errors due to numerical extrapolation & thermal/structural/optical mapping
  - Incorporate Modeling Uncertainty Factor (MUFs) when a credible basis exists (dynamics)

Integrated Modeling & Analysis Process



Cycle 1 Analysis Results Goals

Priorities (in descending order of importance)

1. Estimate system performance & margins relative to the error budget (p.16)
   - Analyses of baseline design under nominal operating conditions
   - Assessments of off nominal design and/or operating conditions
   - Comparative analyses of alternate design options for trade studies p.18

2. Investigate performance sensitivity to driving system design considerations and constraints (p.17)
   - Perturb key design parameters and evaluate perf. improvements
   - Assessments traceable to baseline design models

3. Establish and refine derived key design requirements or constraints for elements, interfaces, and systems (p. 19)

Cycle 1 Modeling & Analysis Products

Models

③ done

1. Assemble & verify integrated system model of baseline design
   - Deployed system configuration (Mid-Fidelity common model for all disciplines)
   - Launch mechanical configuration (Simplified system, Hi-Fi PM quasi-static stress)
   - Preliminary stray light assessment

③ in work

2. Preliminary models of alternate designs for trade studies
   - Good for cursory structural, thermal or optical analyses to mitigate margin problems or optimize performance

Analyses

③ almost done

1. Performance margins results for following
   - Deployed system WFE & Contrast stability under nominal conditions
   - Pointing control system performance
   - Stowed launch performance & stress margins

③ in work

2. Performance sensitivity results for deployed system WFE & Contrast stability sensitivity to:

   Optical bandwidth, CTE variations, OTA mass distribution, PMA mount/launch lock configuration, System fundamental frequencies, SMA control system performance, PMA TCS (Thermal Control System) variability and to sunshield effective emissivity ….

③ to be done

3. Derived key design requirements or constraints for following:
   - Vibration isolation and SMA control requirements
   - Deployed system fundamental frequencies
   - Deployed system PMA TCS stability requirement
   - Etc …

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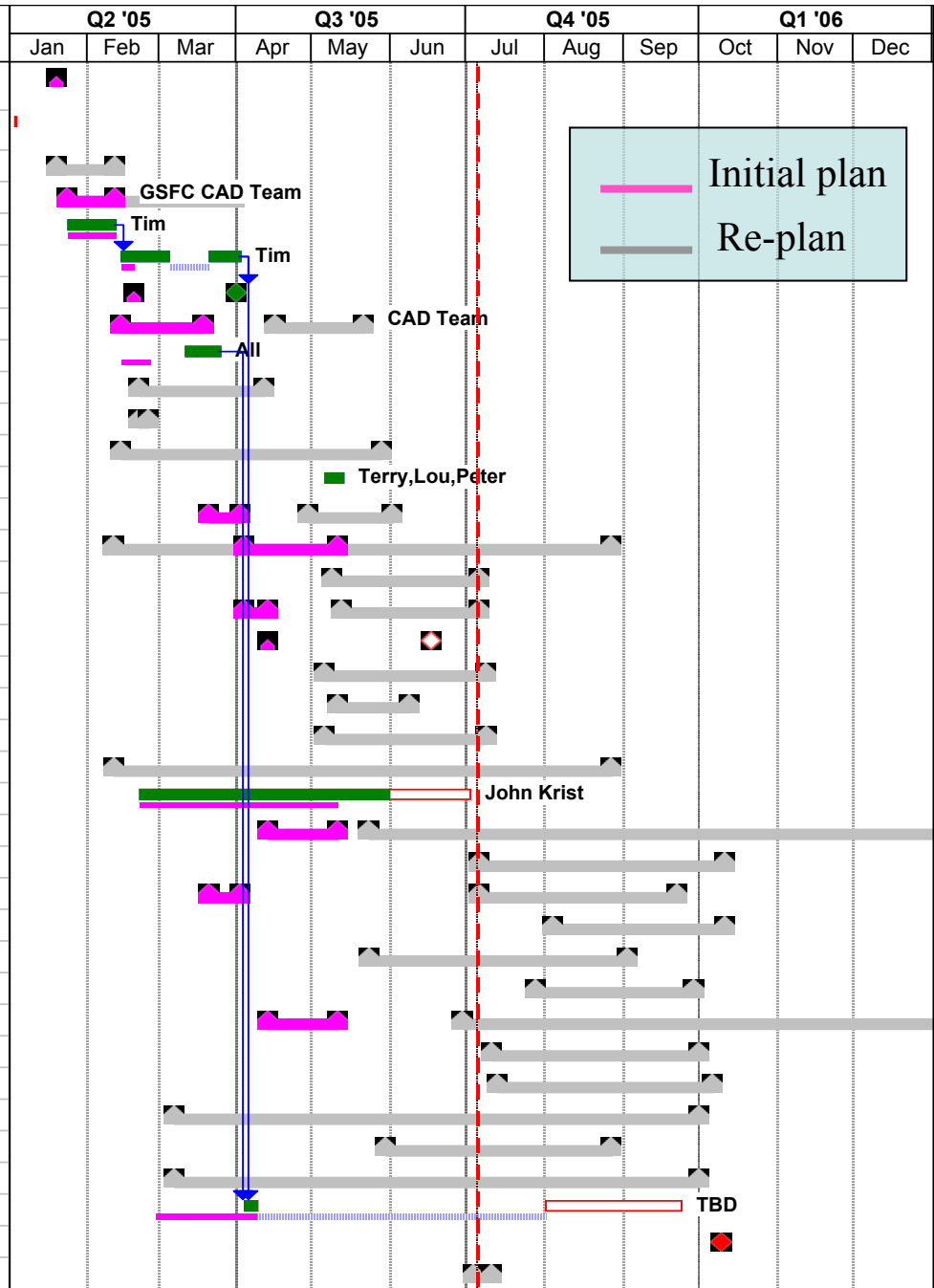
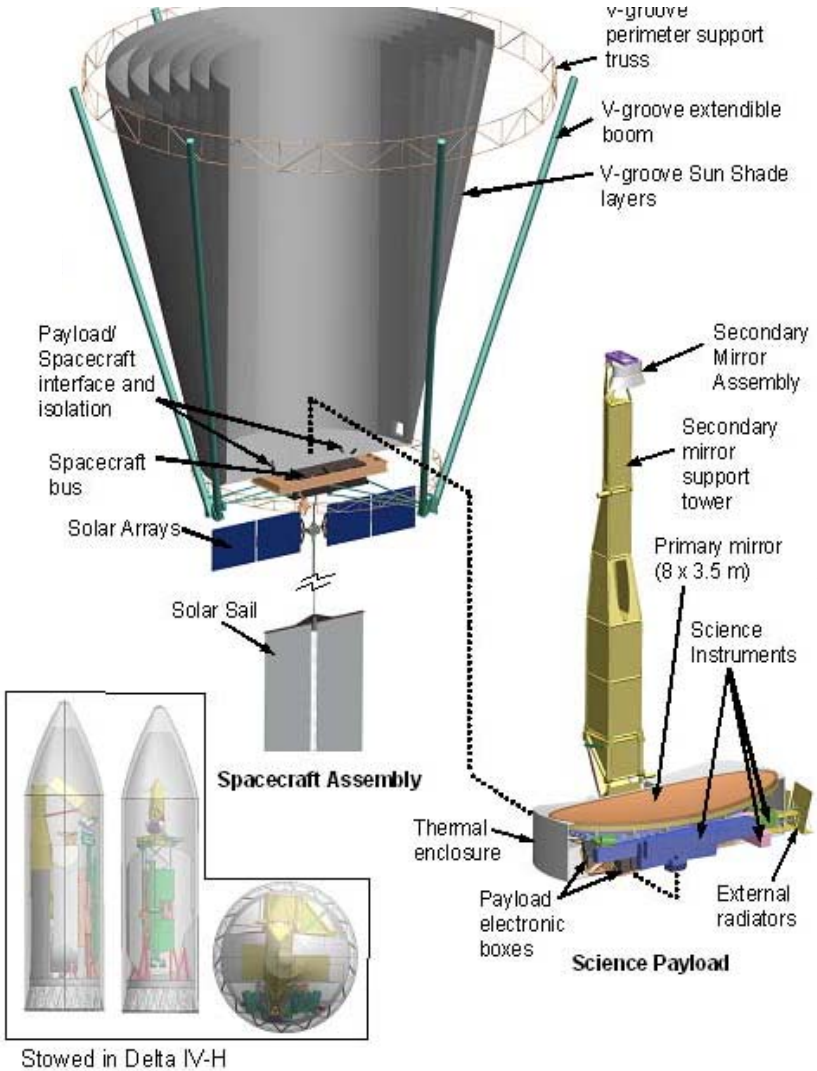
Cycle 1 Schedule Summary

ID	Name
1	TPF-C Flight Baseline Analysis Cycle 1 : FB1
2	FB1 FLIGHT DESIGN & ANALYSIS
3	FB1 Design Definition
9	OTA CAD Model
51	Coronagraph & S/C CAD Model
52	System CAD Model, Operation
53	Freeze Baseline Design
54	Launch Model
57	Material Properties Defined, Design Information For Modeling
58	Build FE Mesh
65	STDT #1
68	Build & Verify Models
78	Define Observational Scenario: Nominal & Bounding Performance
79	Initial Model Outputs & Deliverables
84	Integrated Analysis: Nominal Performance
85	System Temperatures
93	Thermal Distortion to WFE
98	Deliver Nastran temps & distortions to OTA
99	PCS & Dynamics
100	Jitter to WFE studies from RWA imbalance
103	Rigid Body / LOS Performance
110	Optical & WFSC
125	Planet Detection Simulation
126	System Studies
127	System Structures
128	System launch analysis
137	System Sensitivities & Requirements
141	Mech Design Options for Cycle 2
146	Launch-to-orbit commissioning
153	System Thermal Stability and Control (SM, AMS, PSS, …)
168	PCS Sensitivities & Requirements
172	Optics
183	OTA Studies
184	PM Performance
193	OTA Design Options for Cycle 2
200	Straylight Analysis
201	FB2 Start
202	STDTAnalysis Presentation



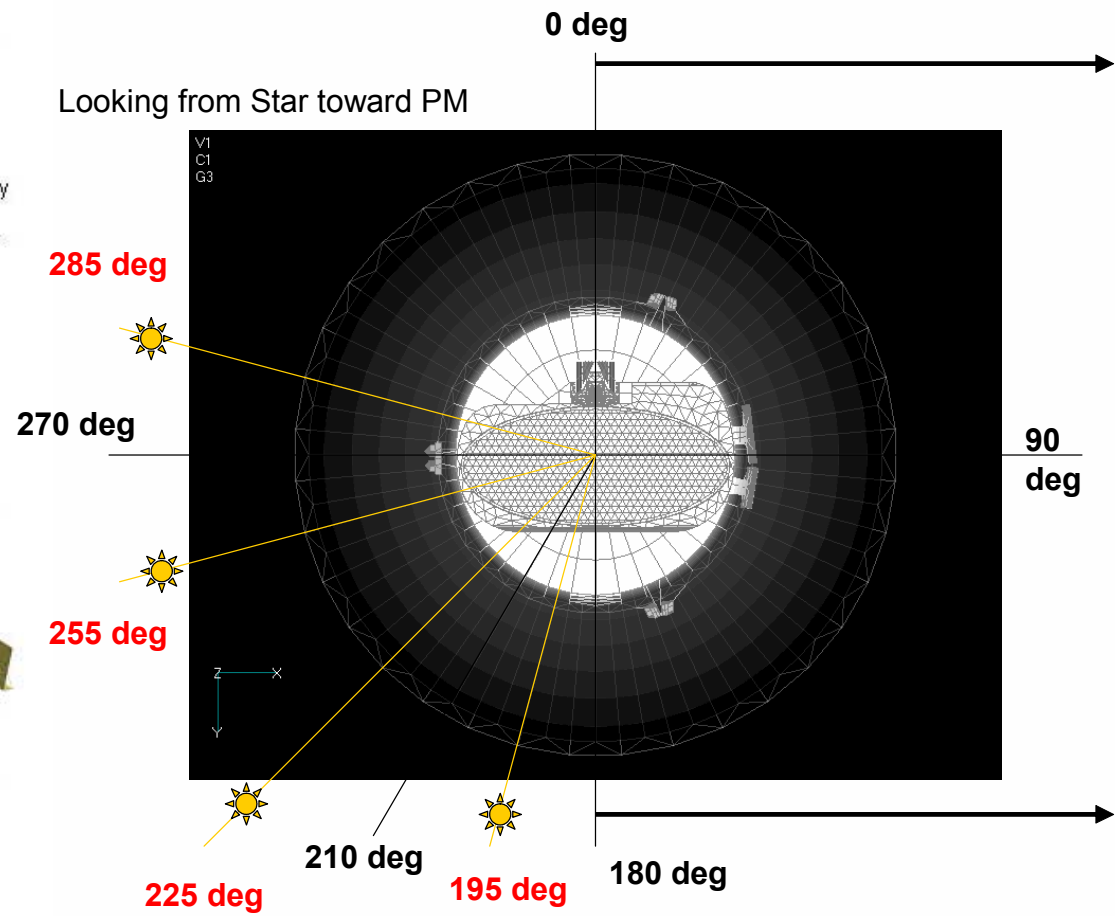
Cycle 1 Design for Core Analyses

Configuration BV1d-D frozen 4/1/05



Nominal Observing Angles

60° roll with ± 15° dithers



Reminder

- This is work in progress and not all tasks are completed to evaluate Cycle 1 design and formulate Cycle 2

… But

  - *there is an extensive plan that delineates the path to completing Cycle1 into Cycle 2. Still 2½ months to go!*
  - *Tasks are on schedule and progressing as planned*

- The preliminary results look very promising especially for on-orbit performance, some aspects of launch design still need to be worked out

…. But

  - *we are diligently working through the problems and are investigating solutions as necessary*
  - *The designs will be improved and models become more detailed as we move towards Phase A.*

- We are open to suggestions and recommendations

BACKUP SLIDES

Nomenclature

- **Cycle n** = the period starting with the definition of an updated design concept and ending with completion of its performance evaluation and alternate design option assessments.
- **Model** = numerical representation of the design
- **Analysis** = exercising the model to environmental conditions to extract performance metrics of interest
- **Model Verification** = model conforms to what was designed and interfaces with each component as expected (e.g., model consistency checks)
- **Model Validation** = demonstration that model predicts the behavior of the intended design & physics (e.g.test correlation)

Current Status

- Cycle 1 plans defined and tracked, Cycle 2+ plans in progress
- Effective team communication & model exchange established
- All FB1 models complete
  - Integrated FB1 design stowed & deployed
  - Discipline models verified
- FB1 nominal performance evaluation complete
  - Deployed WFE and Contrast stability to thermal and jitter environment
  - ACS pointing margins
  - Launch stress evaluation
- Performance sensitivity studies in progress
  - CTE variations, fundamental frequencies vs mass vs optical performance, optical bandwidth effects, mounts & launch restraints, …
- Key control design requirements not yet quantified
- Where performance is marginal alternate designs & trade studies have been proposed/planned and analyses in progress

Analyses for Performance & Margins

Priorities (in descending order of importance)

1. Deployed condition thermal/structural induced optical errors
   - System errors (e.g., rigid body motion driven WFE)
   - Optics figure error (e.g. quilting of PM w/ high fidelity model)
2. Deployed condition jitter margins
3. Deployed condition pointing control and stability margins
4. Stowed condition launch load margins
   - System analyses of significant contributing modes
   - Quasi-static stress analyses of PMA
5. Deployed condition PM thermal control margins
6. Ground test condition margins for PM figure verification approach – includes 1-G sag

Analyses of Performance Sensitivities

Priorities (in descending order of importance)

1. Deployed optical performance sensitivity to key design parameters: e.g., uncertainties in material properties (nominal, variations), mass & frequencies, temperature variations (bulk, gradients), sunshield v-groove separation / circularity/ emissivity, mounting/support features ….
2. ACS performance sensitivity to sensor noise, mass props, vib isolation,…
3. Deployed System/SM tower fundamental modes sensitivity to uncertainties in System/SMA mass, material properties, deploy/lock mechanism stiffness, etc
4. Mass margin sensitivity to SMTA f_n, PMA f_n (stowed, on-orbit), active/passive isolation, SMA stroke, mount/support features, ….
5. Deployed and ground condition PM modal content sensitivity to uncertainties in PM mass, PM build, PM mounting, thermal states
6. Deployed condition PM thermal/structural deformation sensitivities to uncertainties in thermal control (spatial, temporal), thermal gradients, …
7. Deployed condition OTA optical error sensitivities to sunshield effectiveness uncertainties (BOL/EOL, degradation, etc)
8. Optical performance sensitivity to BOL/EOL degradation, wavelength,

Cycle 1 Trades Supported by Analyses

Key Trades Supported by Analyses

1. Closed-back vs open-backed
2. RWA design option trades
3. PM architecture: elliptical vs race track
4. PMA launch support
5. Sunshield architecture: conic vs sugar scoop
6. PMA core segmentation (hex versus square)
7. Actuated PMA versus coarse DM
8. Sunshield circularity

Analyses to Derive Key Requirements

Priorities (in descending order of importance)

1. Derived mechanical properties from thermo-optical performance: e.g., CTE (bulk and variability) constraints or temperature gradients
2. Thermal control requirements
   - Constant temperature boundary, Constant power boundary, Discrete heater locations
3. SMA position stability & control requirements
4. Vibration isolation requirements
5. Deployed condition frequency constraints
   - SMTA , PMA, Sunshield , Solar Array and Solar Sail fundamentals
6. Stowed PM requirement for mounts & launch lock supports
7. Sunshield effective emissivity
8. Ground test condition bounds on isolated OTA assembly stability (jitter & thermal environment)
9. Ground test PM requirement for figure actuators, if any
10. Modeling error margin allocation
11. Others TBD

Cycle 1 Alternate Concepts for Analysis

Alternate Design Concepts for Cursory Analyses

1. Passive vs dynamic isolation
2. Racetrack monolithic PMA
3. 8x3m mirror
4. Sugar-scoop sunshade concept
5. PM mounts & launch locks
6. Lightweighted SMA
7. OTA baffle concept
8. Active thermal control layer in sunshield

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nightsky systems

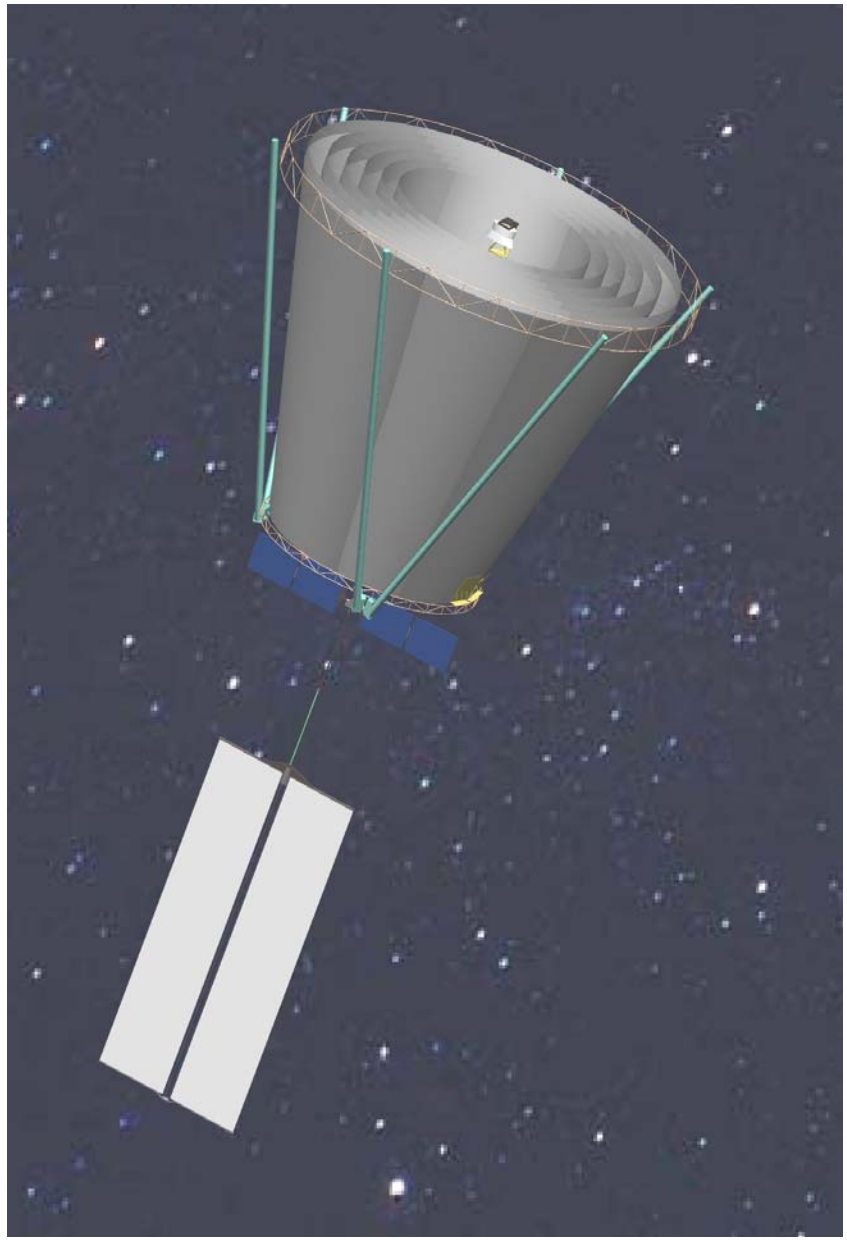
TPF Terrestrial Planet Finder

Performance Modeling for TPF-C

Philip Dumont

Sidd Bikkannavar

David Palacios



11-12 July 2005

Introduction

- **Tasks**
  - **Optical Sensitivity Matrices (OSM)**
  - **System contrast prediction**

- **Personnel**
  - **Sidd Bikkannavar: OSM**
  - **Philip Dumont: OSM and management**
  - **David Palacios: contrast calculations**

OSM: Description

- **Used to characterize the linear response of an optical system to perturbations**

- **Metrics**
  - **OPD in Exit Pupil of occulting mask**
  - **Beam-walk on optical surfaces**
  - **Spot diagram centroid at occulting mask**

Implementation

- **Partials calculated individually for all six degrees of freedom for each optic**
- **Compound optics**
  - **Optics with more than one surface (e.g. beam-splitters)**
  - **Perturbed about common point**
- **Primary mirror surface perturbations**

Implementation

- **Evaluation: numerical partials**
  - **Value of metric for nominal system**
  - **Perturb degree of freedom for an optic and re-evaluate metric**
- **Used by**
  - **Pointing and Control analysts for jitter performance evaluation**
  - **Structures analyst for thermal distortion performance evaluation**
- **How are the sensitivities used?**
  - **Enable rapid WFE estimation from rigid-body perturbations and optics aberrations**
  - **More precise estimation of WFE and contrast requires MACOS-based system contrast performance model**

Rigid-Body Perturbations

Nominal System

Nominal MACOS optical model to occulting mask → OPD at each element → Chief ray intercept: cRNom OPD at mask Exit Pupil: OPDNom

Nominal MACOS optical model to occulting mask → Spot diagram at mask → Spot diagram centroid: cenNom

Perturbed System

Perturb single DOF for optic in nominal MACOS optical model: Δx → OPD at each element → Chief ray intercept: cRPert OPD at mask Exit Pupil: OPDPert

Perturb single DOF for optic in nominal MACOS optical model: Δx → Spot diagram At mask → Spot diagram centroid: cenPert

Beam-walk sensitivity:

$$\frac{(cRPert - cRNom)}{\Delta x}$$

Centroid sensitivity:

$$\frac{(cenPert - cenNom)}{\Delta x}$$

Wave front sensitivity:

$$\frac{(OPDPert - OPDNom)}{\Delta x}$$

Primary Surface Perturbations

Nominal System

Nominal MACOS optical model to occulting mask → OPD at mask exit pupil: OPDNom → Wave front sensitivity:

$$\frac{(OPDPert - OPDNom)}{\Delta p}$$

Perturbed System

Nominal MACOS optical model to occulting mask → PM surface grid for unit amp perturbation of FEM Node → Scaled PM surface grid (Δp) applied to PM → OPD at mask exit pupil OPDPert → Wave front sensitivity:

$$\frac{(OPDPert - OPDNom)}{\Delta p}$$

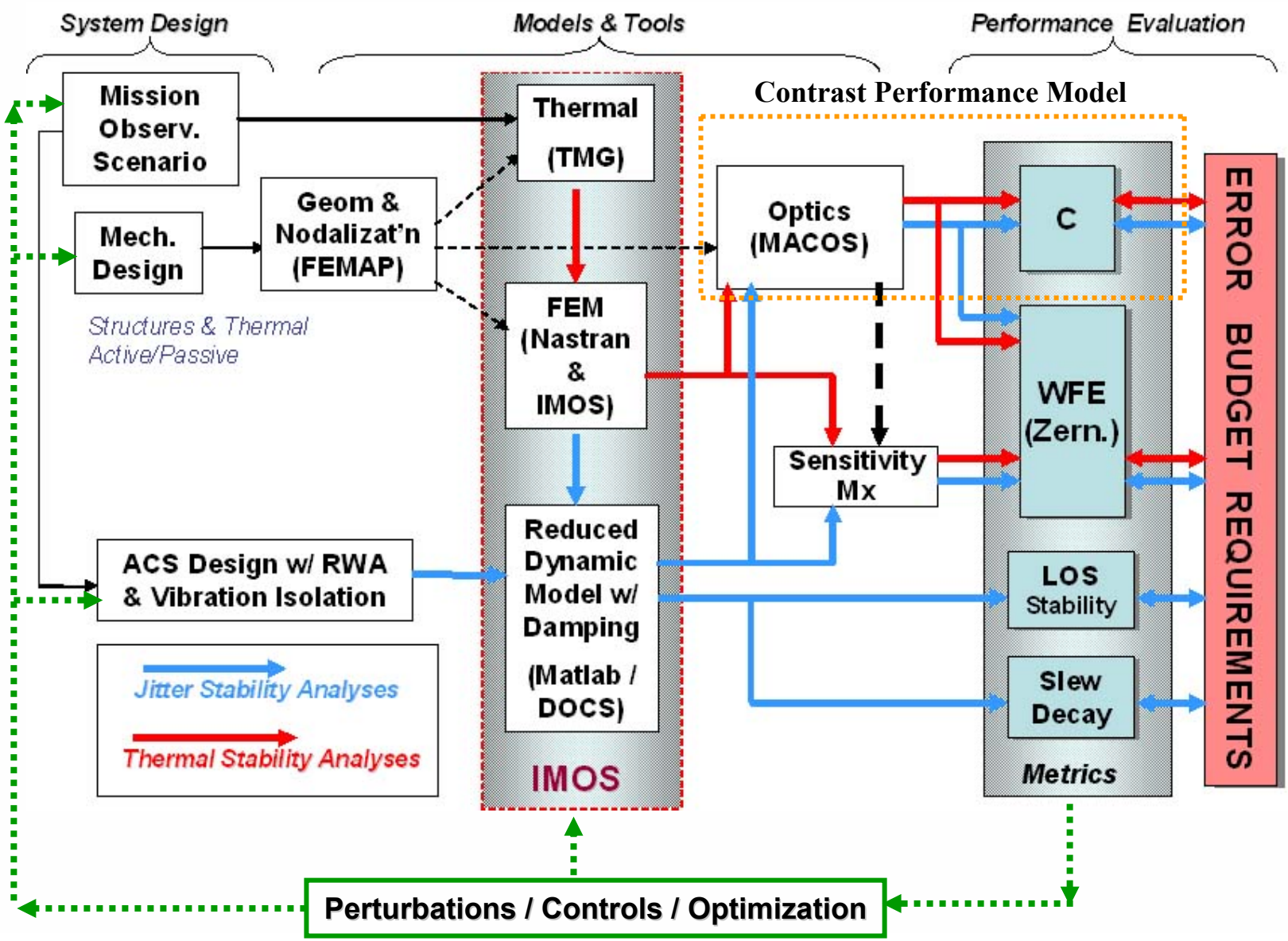
Future Work for Cycle Two

- **Enforce consistent order and normalization for Zernike polynomials**
- **Rewrite MATLAB scripts to make them more efficient**
- **Recalculate OSM for Cycle Two design**

System Contrast Performance

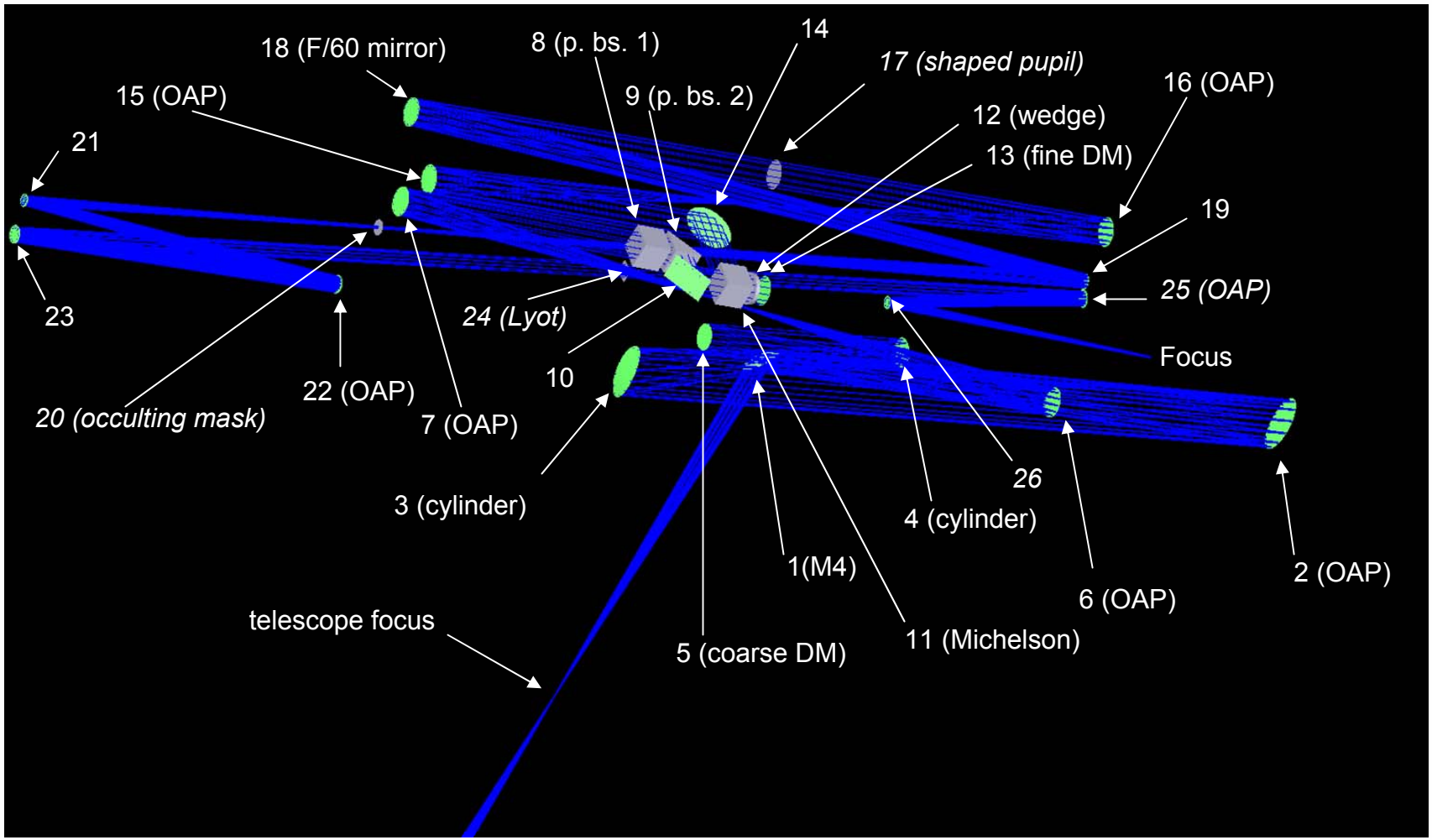
- **Goal**
  - Simulate contrast performance of SSS in presence of representative static and dynamic system perturbations
  - Independent cross-validation of error-budget
- **High-fidelity model of optical system**
  - MACOS optical model derived from ZEMAX model of FB1 design
  - Near-field diffraction between all important surfaces
  - 8th order mask with corresponding Lyot stop
  - Representative surface errors on all reflective elements up to Fine DM: based on PSD functions in error-budget
- **Iterative wave front control/speckle nulling algorithm implemented**
- **Broad-band contrast ($\Delta\lambda/\lambda \sim 0.2$) vs. λ/D**
- **Contrast degradation from quasi-static thermally induced perturbations and dynamic perturbations**
  - Rigid-body perturbation to optics
  - PM surface figure

Integrated Modeling & Analysis Process



Backup Slide

Optical System



TPF Terrestrial Planet Finder

LOCKHEED MARTIN
Ball Aerospace & Technologies Corp.
NORTHROP GRUMMAN Space Technology
TC Technology
nightsky systems

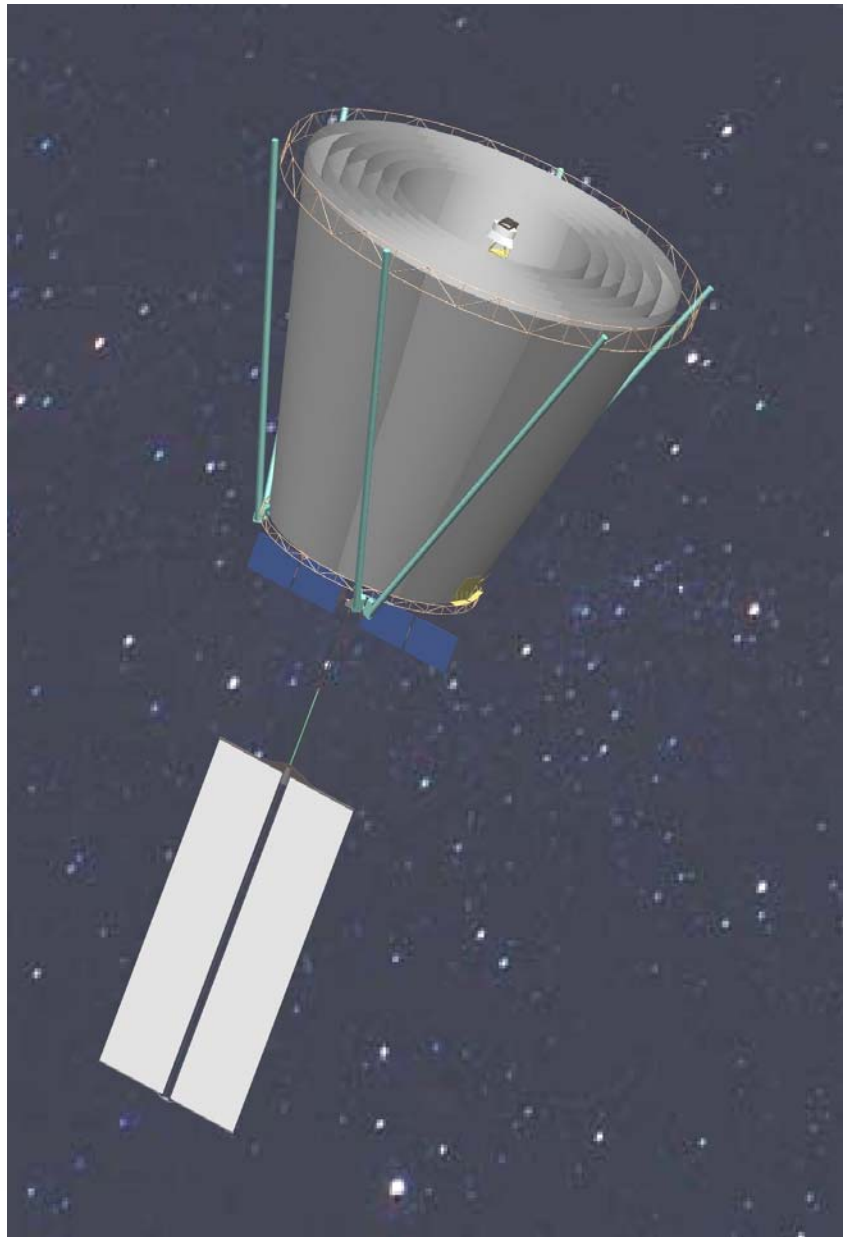
TPF Terrestrial Planet Finder

TPFC System Performance Model

Dr. David M. Palacios

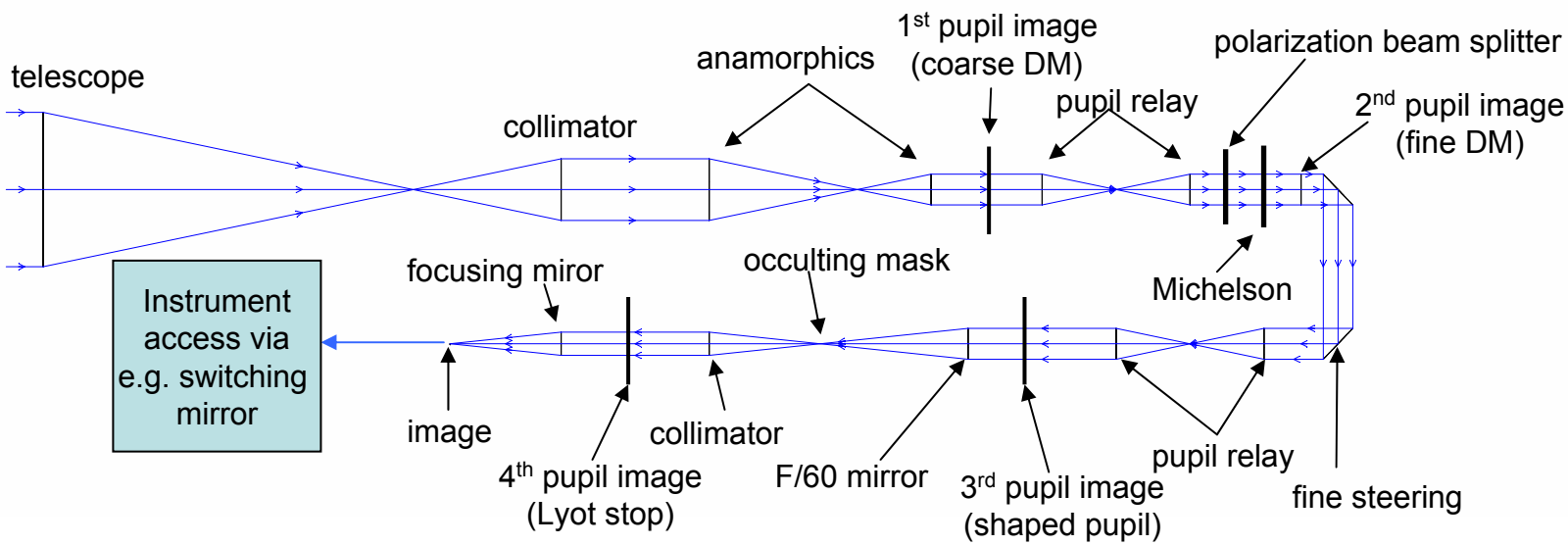
Contributors:
Phillip Dumont
Joe Green

11-12 July 2005



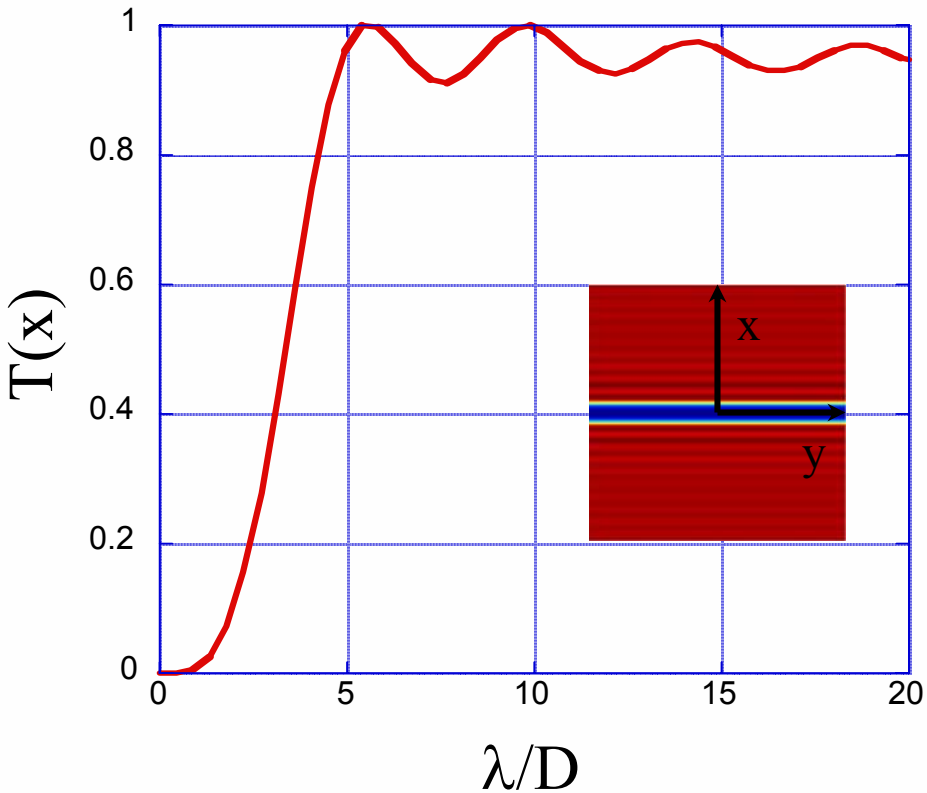
Performance Modeling Capabilities

- Folded model with near field diffraction between important surfaces up to the Occulter. (using MACOS package)
- 8th-order mask and matching Lyot stop are implemented
- Surface maps applied on all reflective optics
- Rigid body motions of all optics with 6 degrees of freedom
- Model contains a 2DM Michelson WFC architecture with a full dark hole iterative nulling algorithm
- Broadband simulations
- Model can also include shaped pupil masks and amplitude aberrations without position perturbation capability
- Outputs contrast as a final metric of system performance

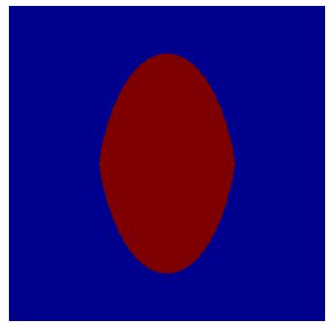


The 8th Order Mask and Lyot Stop

8th Order Linear Occulter



Cat's Eye Lyot Stop

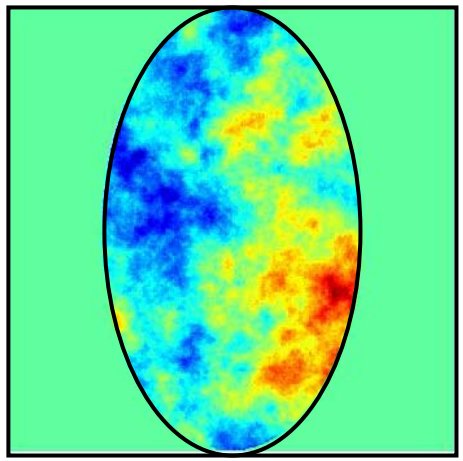


Efficiency

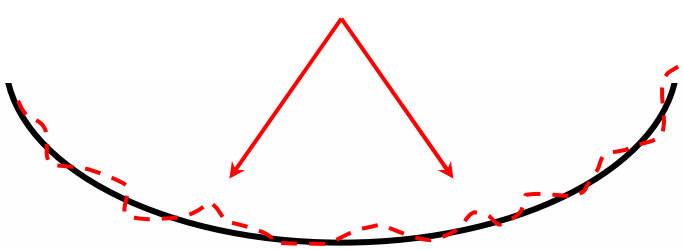
42%

Small Figure Errors

Surface Map



Small Deviations from an ideal surface



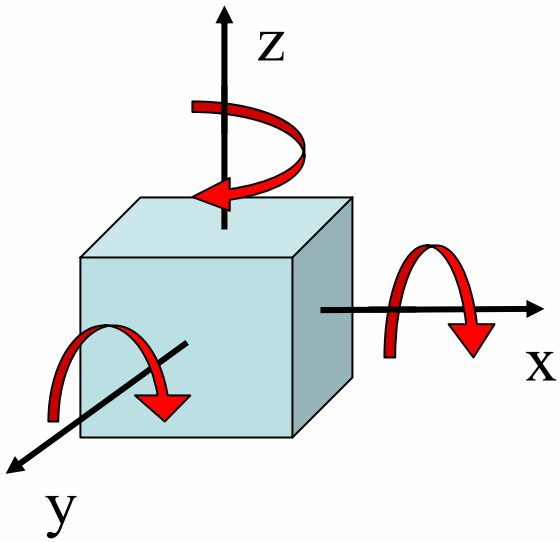
$$PSD = \frac{\sigma^2}{N_0\left[1+\left(k/k_0\right)^3\right]}$$

N_0=total Integrated PSD

k_0=PSD cutoff frequency

σ=root mean square value of the wave front error

Rigid Body Motion



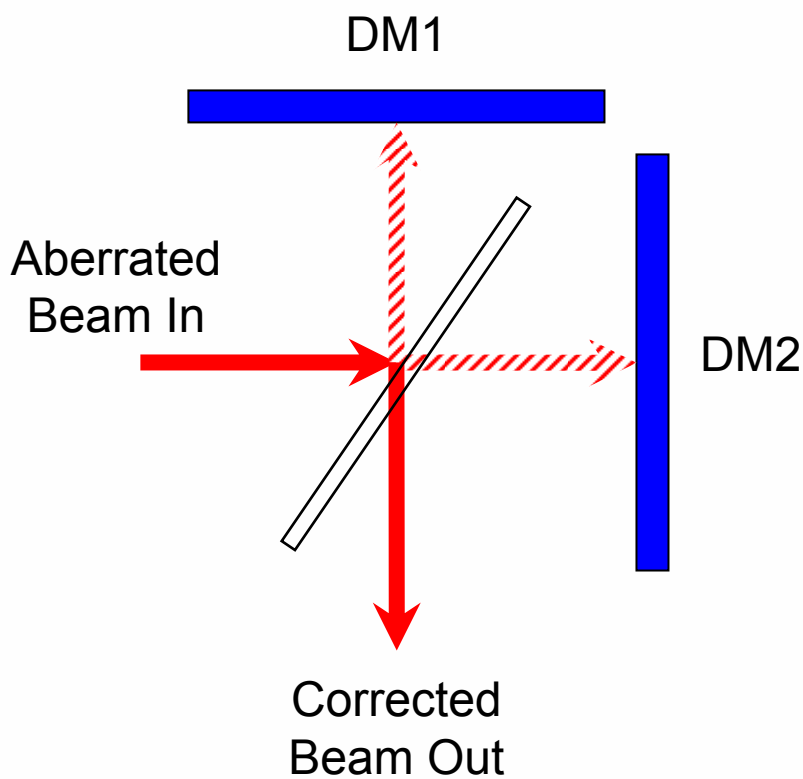
Multi-surface optics rotate
About a common point

Surface Maps move
with the Optics

6 degrees of Freedom:
3 translation: x,y,z
3 rotation: θ_x, θ_y, θ_z

Used to model:
Thermal misalignment of optics
Jitter Analysis

WFC with A 2-DM Michelson Interferometer



Spatial Frequency Band Limit

64 cycles/aperture

Wavelength dependent!

$$E_{in} = A_{in} \exp\left(i \frac{2\pi}{\lambda} OPD_{in} \right)$$

$$OPD_C^{\phi} = -OPD_{in}$$

$$OPD_C^{A} = \frac{\lambda}{2\pi} \cos^{-1}\left(\frac{A_{\min}}{A_{in}} \right)$$

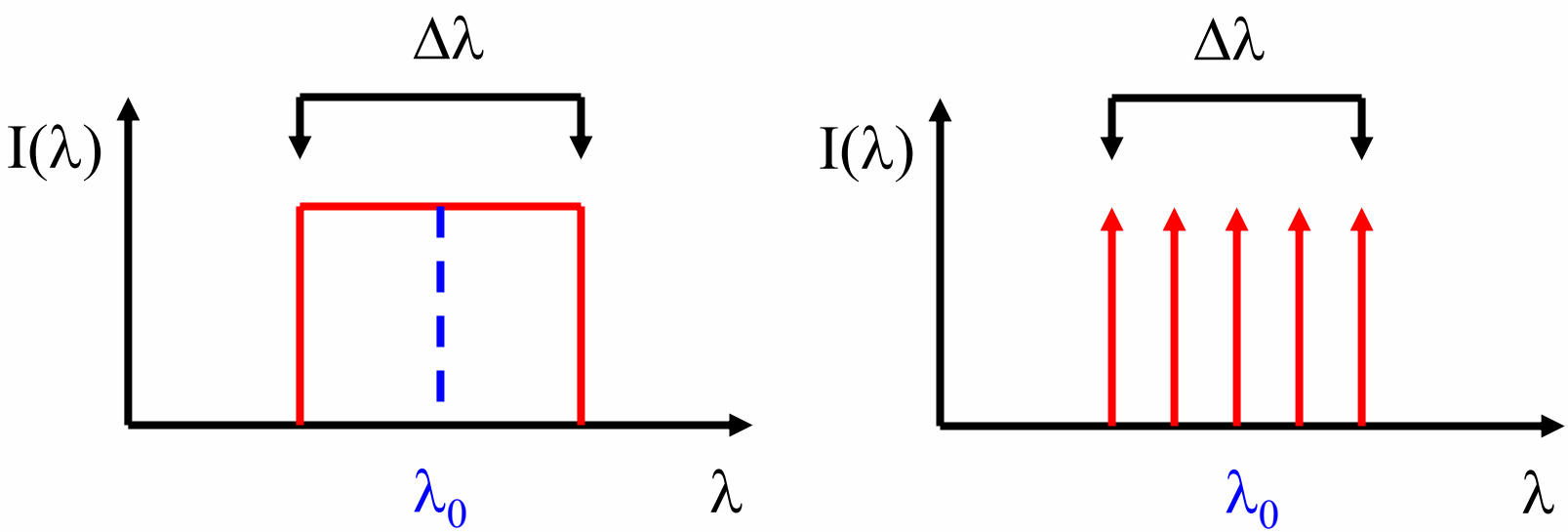
$$S1 = OPD_C^{\phi} + OPD_C^{A}$$

$$S2 = OPD_C^{\phi} - OPD_C^{A}$$

$$E_{out} = E_{in} \left[\frac{1}{2} \exp\left(i \frac{2\pi}{\lambda} S1 \right) + \frac{1}{2} \exp\left(i \frac{2\pi}{\lambda} S2 \right) \right]$$

$$E_{out} = A_{\min}$$

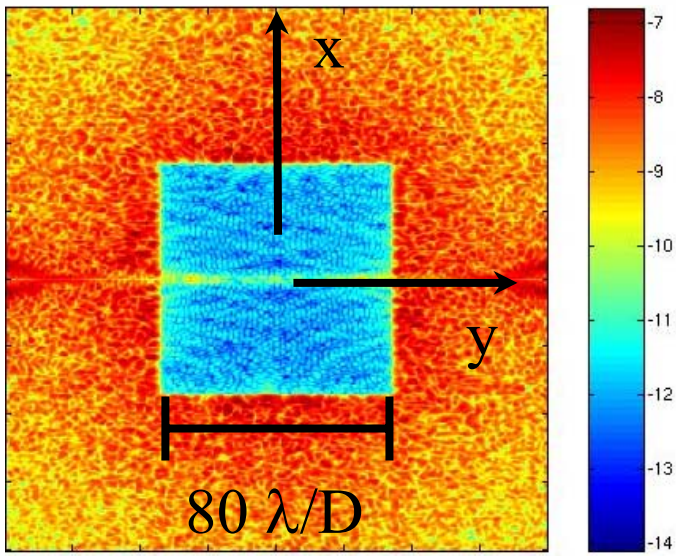
The Source Spectra



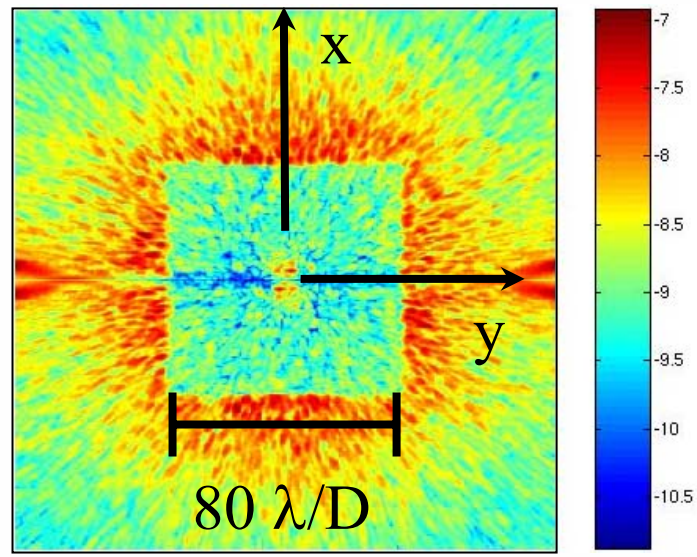
Phase and Amplitude are corrected at λ_0 at an Exit Pupil

Contrast With Static Figure Errors

$\Delta\lambda = 0$nm



$\Delta\lambda = 30$nm



Contrast at $4\lambda/D$

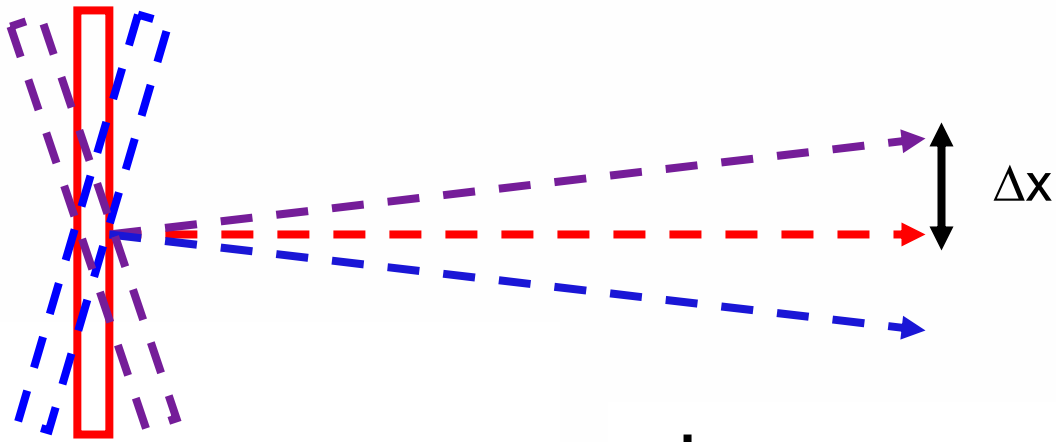
5×10^{-13}

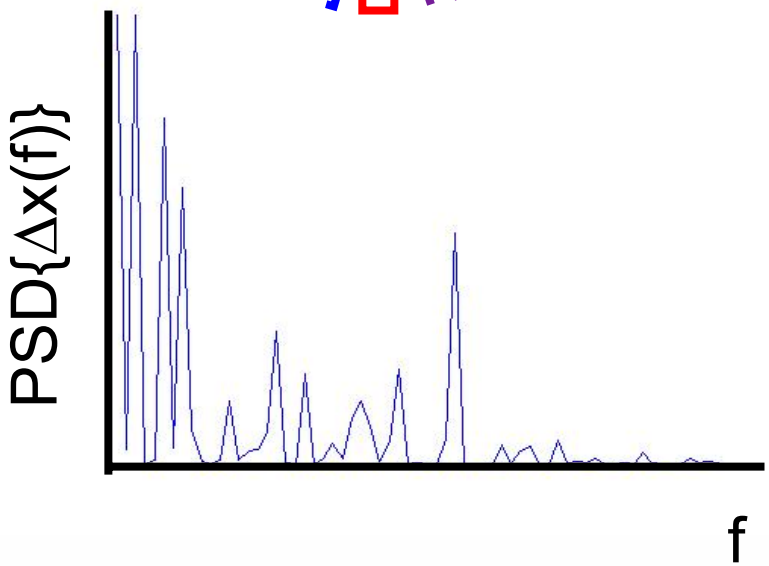
4×10^{-09}

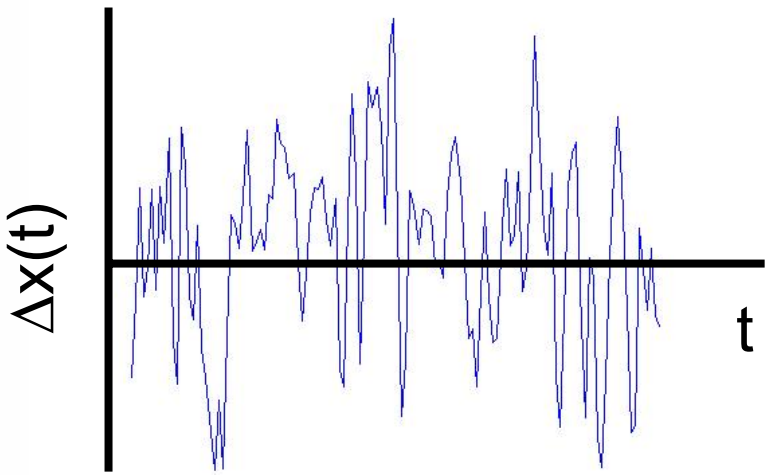
WFC is not optimized for Broadband!

Jitter Analysis

Jittered optic moves the spot on the mask

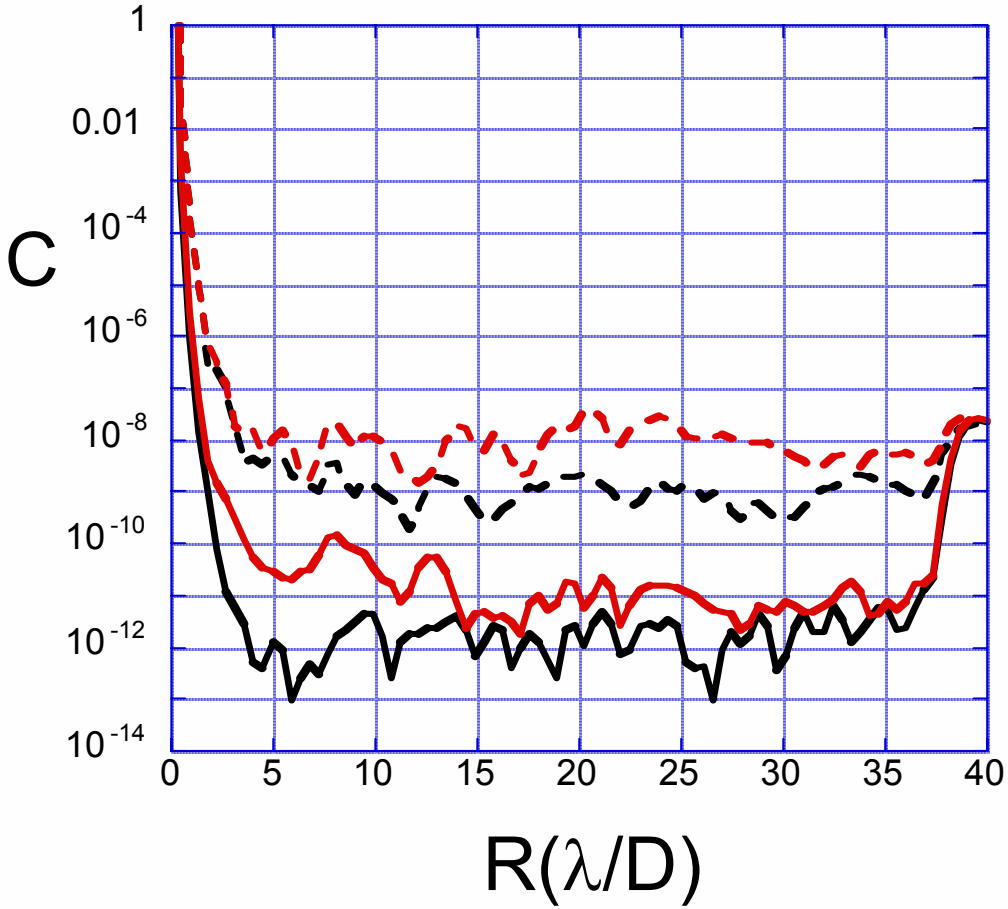






Contrast with Jitter

Preliminary Results!



Jitter On

- Δλ= 0nm
- Δλ= 30nm

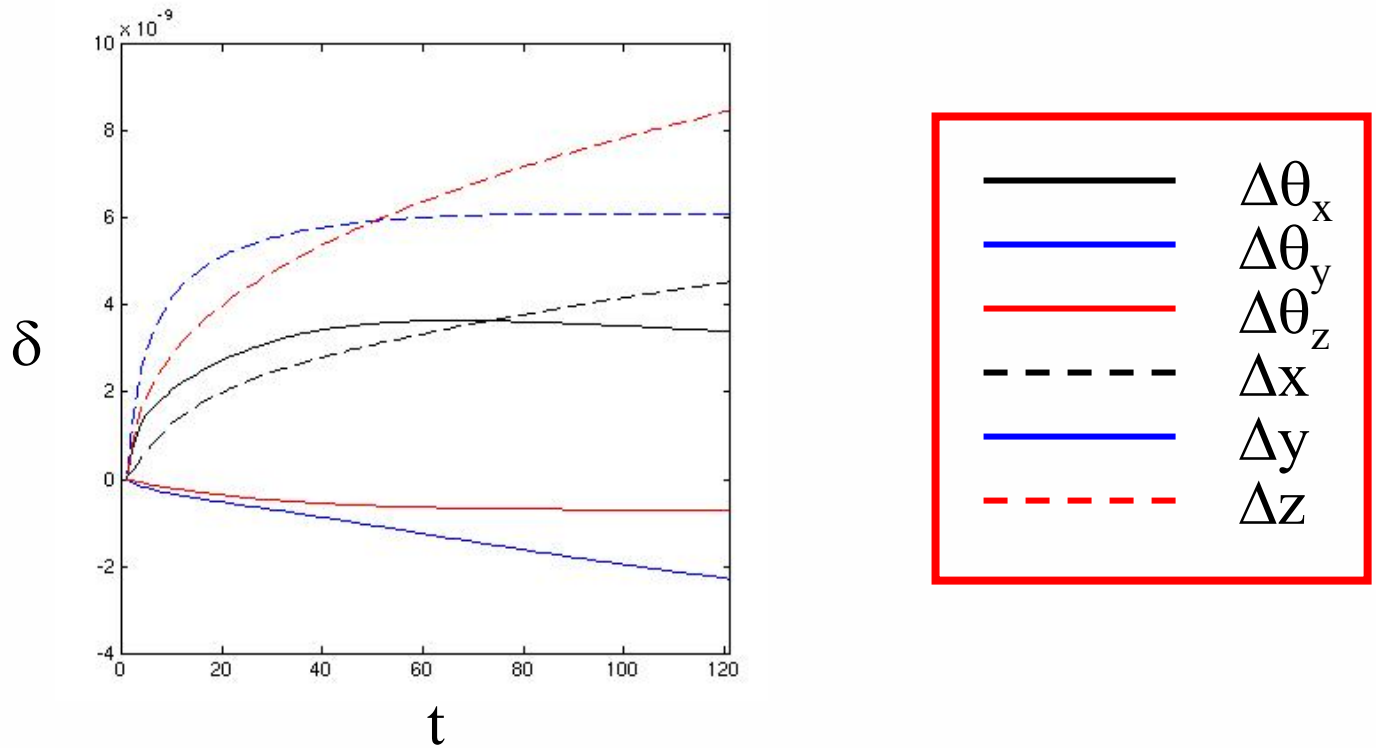
Jitter Off

- Δλ= 0nm
- Δλ= 30nm

Thermal Misalignments after 30^0 Roll

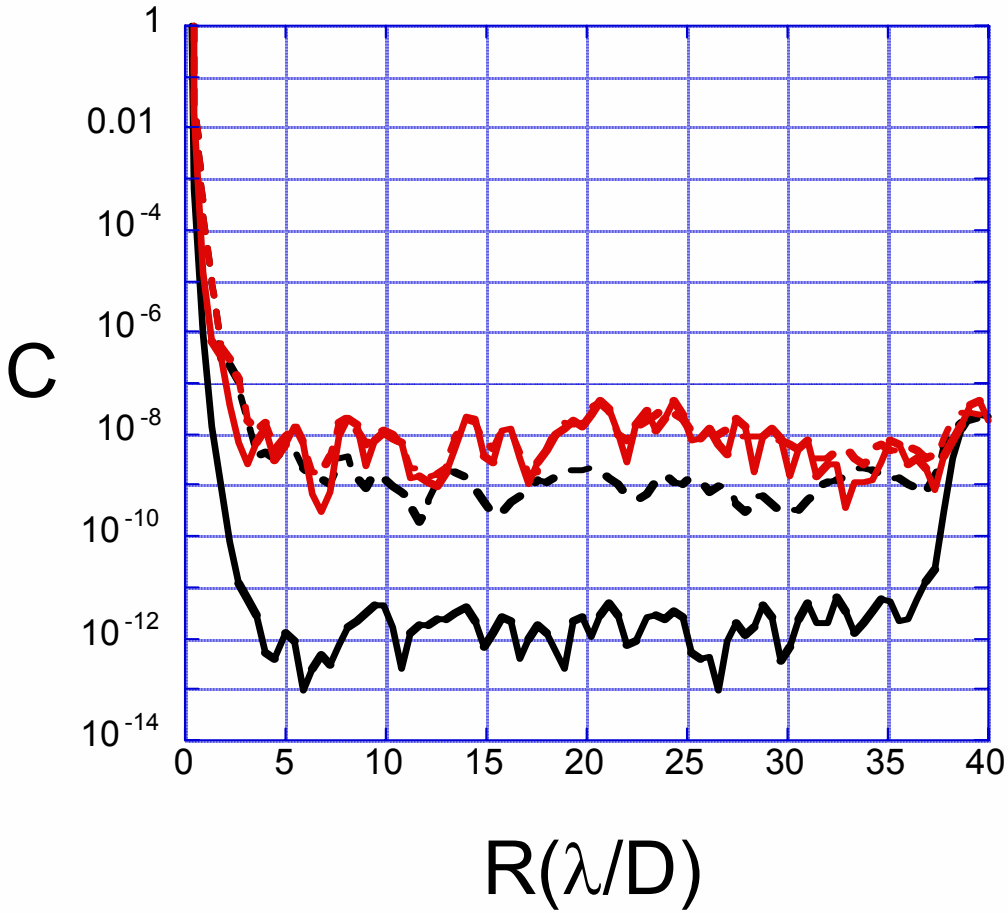
Pointing Control not yet fully implemented!

Rigid Body Displacements



Contrast with Thermal Misalignments

Preliminary Results!



Thermal On

- Δλ= 0nm
- Δλ= 30nm

Thermal Off

- Δλ= 0nm
- Δλ= 30nm

Future Work

Model Upgrades

- Reduced Noise Floor is the first priority
- Inclusion of Mask Errors
- Proper modeling of Cylindrical Optics
- Add pointing control correction
- Inclusion of amplitude errors without position perturbation capability

Future Studies

- Thermal and Jitter analysis with deformations on the Primary Mirror
- Broadband WFC optimization
- Error Budget Validation

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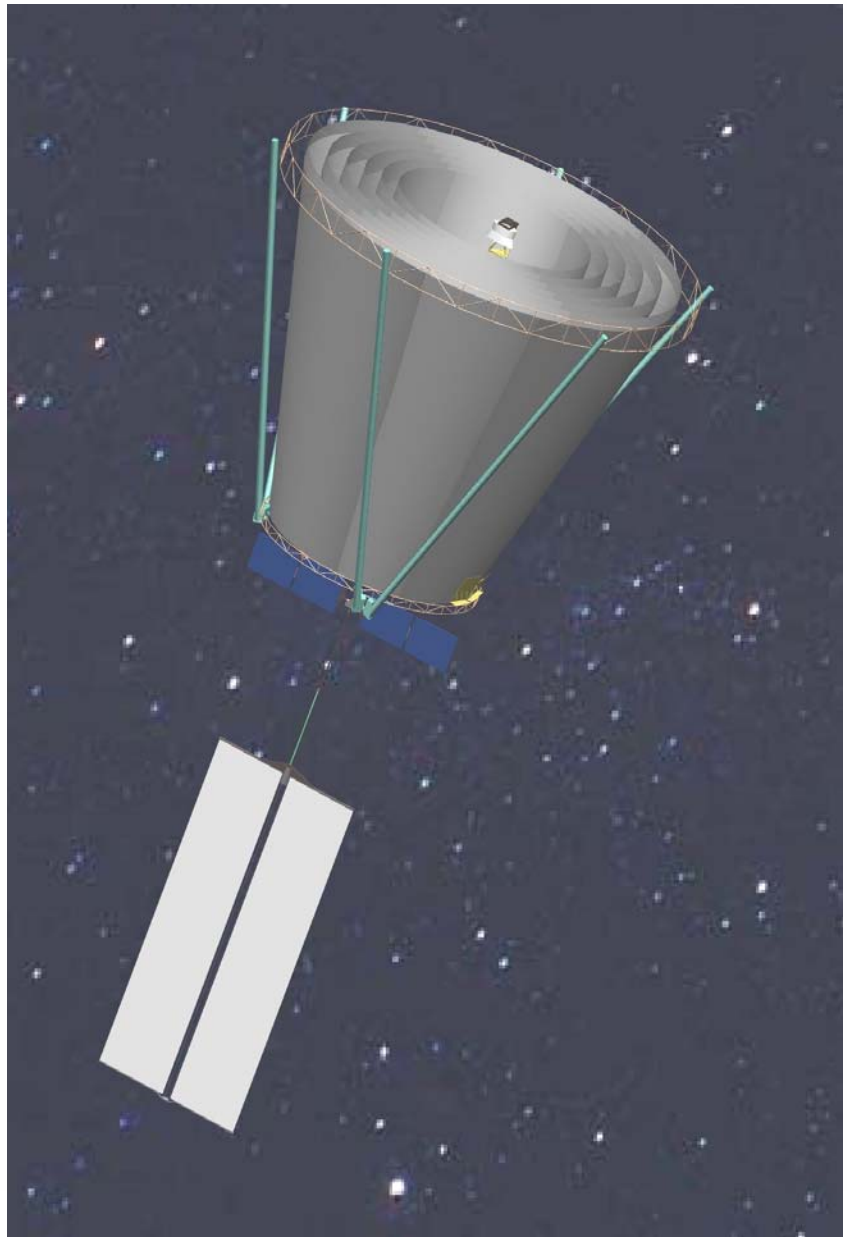
System Thermal Modeling & Performance

Eug Kwack

Contributors:

Michael Saeger (ATA), Andy Kissil, Tim Ho, Terry Cafferty

11-12 July 2005

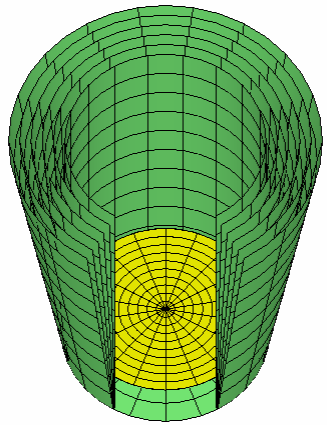


Outline

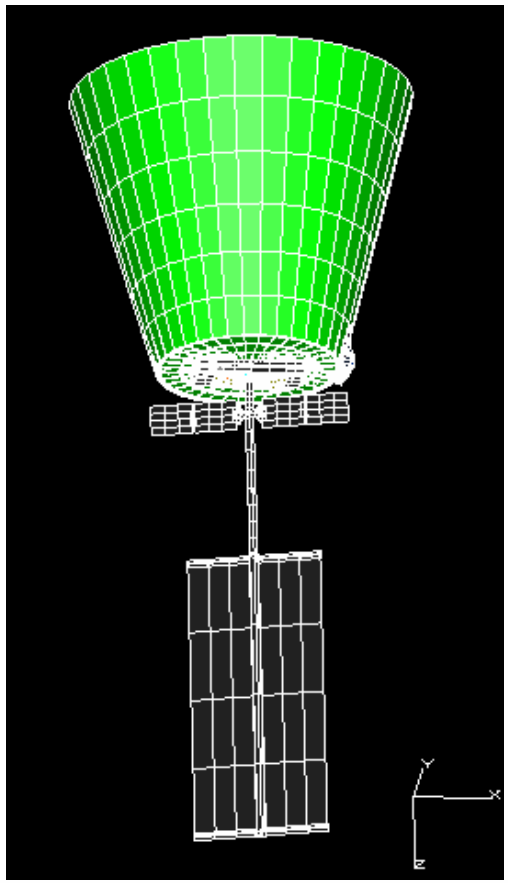
- Thermal Tools
  - TSS/SindaG, TMG, IMOS
- Thermal Models and Run Information
- Steady Results at 195 deg Sun Angle
- Delta-Temperatures for 30 deg Dither
  - Temperature differences between two steady-states of the beginning and end following a 30 deg Dither
  - Transient Results of PM during 30 deg Dither
- Temperature Control Heater Powers
- Conclusions and Future Work

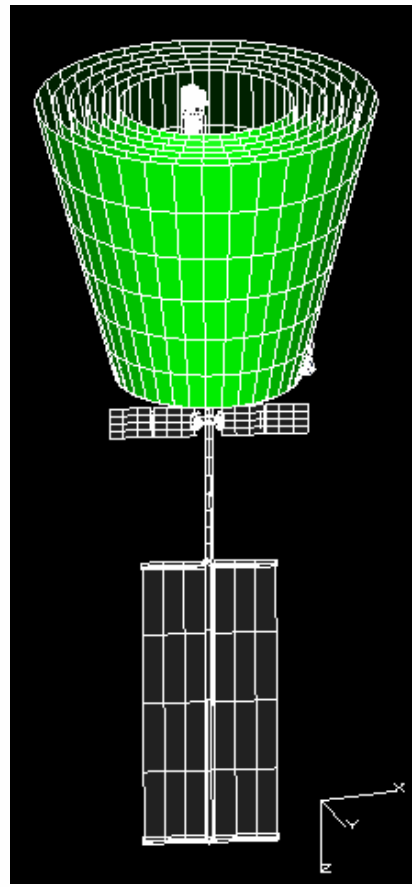
Thermal Tools used

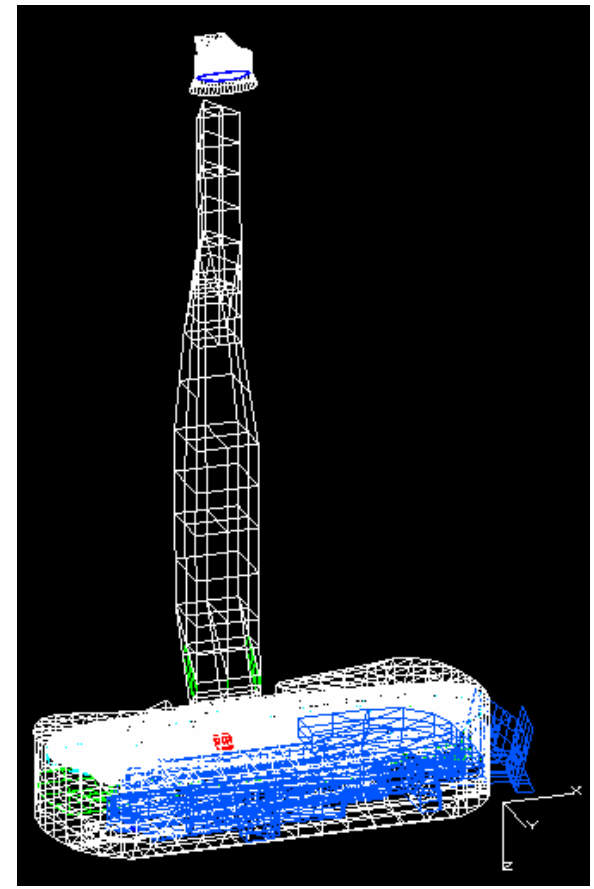
- TSS/SindaG and TMG
  - TSS: Thermal Synthesizer System
  - SINDA: System Improved Numerical Differencing Analyzer
  - TMG: Thermal Model Generator
  - A simplified model was used to investigate the effects of specularity, spacing between layers and angle between layers of sun shield. Both TMG and TSS/SindaG were used.
  - In FB1 study, TMG is used for faster run time and better data exchanges with other tools.
  - Double precision version of TMG is available (I-DEAS11)
  - Eventually IMOS (Integrated Modeling Optics Software) will be used once it is ready.



TMG Thermal Model



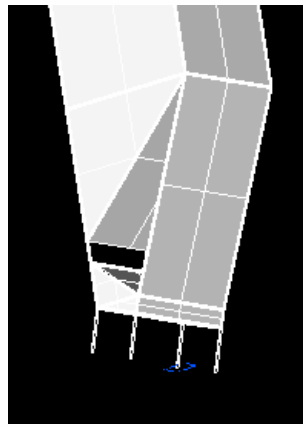




Number of Nodes: 18,180
Number of Elements: 39,517 (2,654 beams, 3,662 solids, 32,201 thin shells)

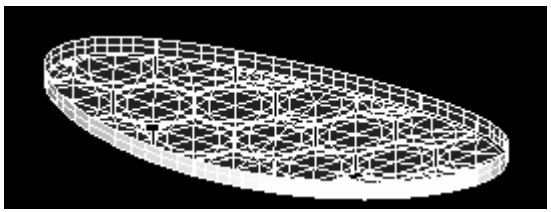
Temperature Control Heaters

Heaters	Set Temp*, °C
PM Bot Heaters	22
PM Side Heaters	22
SM Top Heaters	22
SM Side Heaters	22
M3 Back heaters	22
Thermal Enclosure Heaters	17
SST Mounting Beam Heaters	17

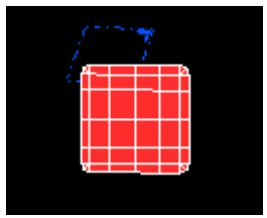


SST Mounting Beam Heaters

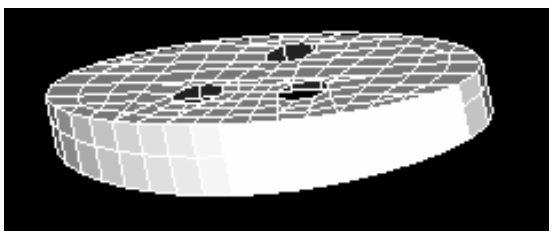
*** In FB1, constant temperature BC's are imposed.**



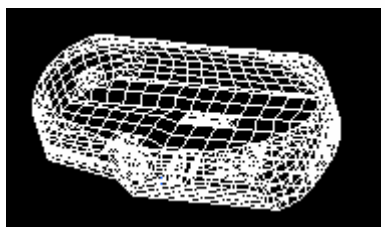
Primary Mirror (PM) Heaters



Tertiary Mirror (M3) Heaters

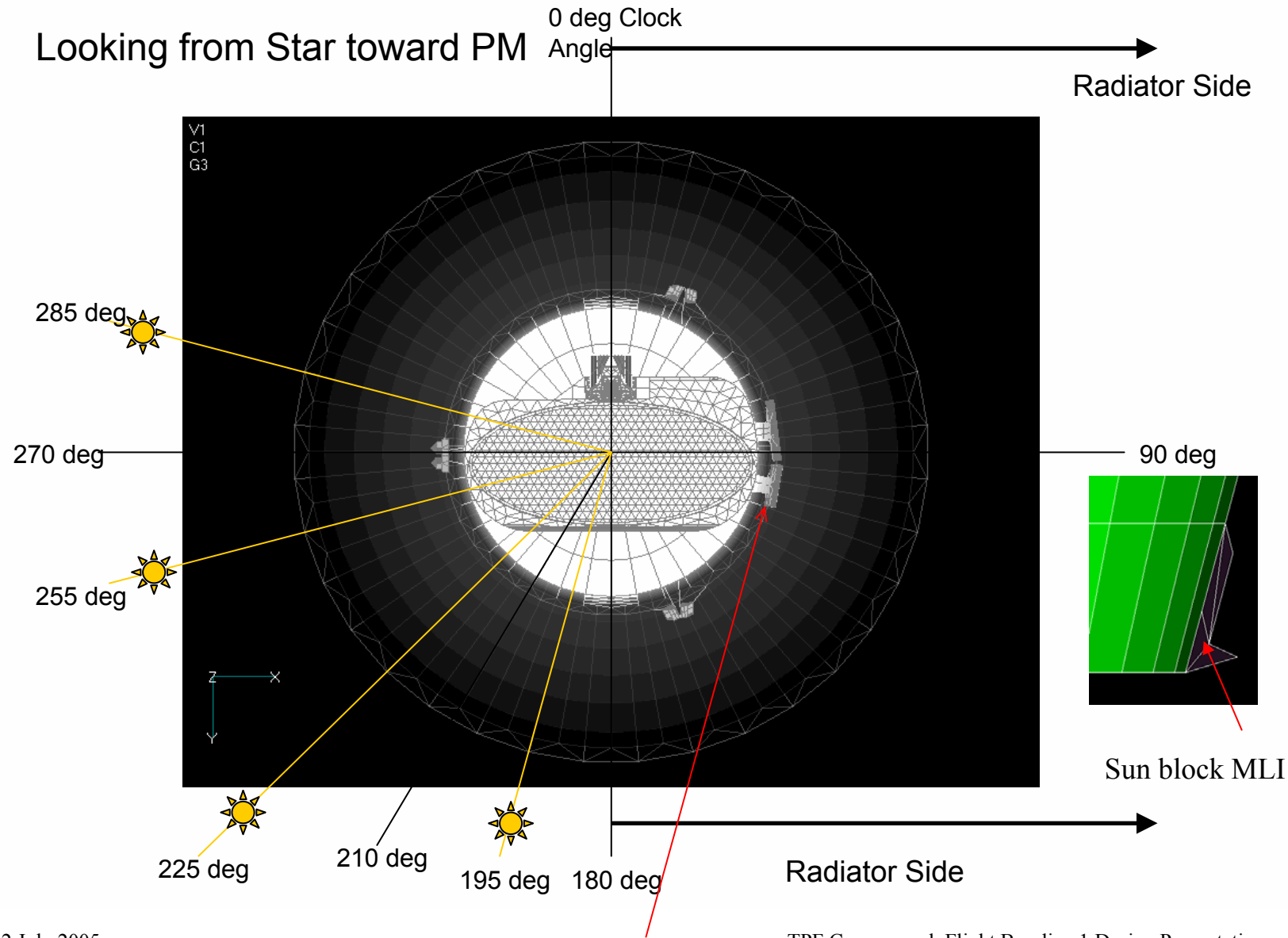


Secondary Mirror (SM) Heaters

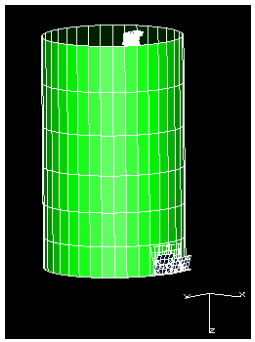


Thermal Enclosure Heaters

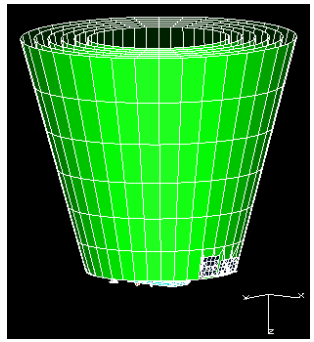
Clock Angle Definition from Andy



Run Information with Thermal Community Workstation



Internal Enclosure



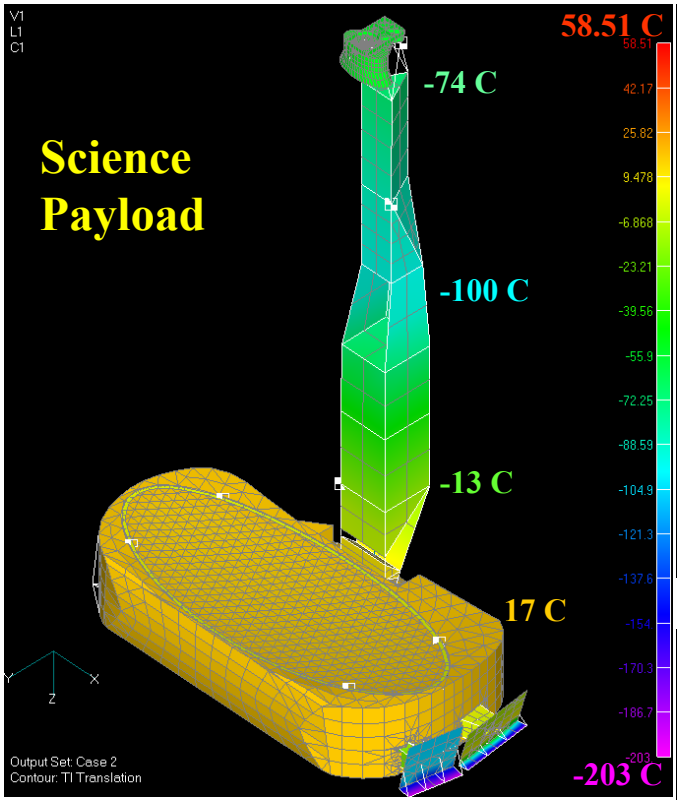
External Enclosure

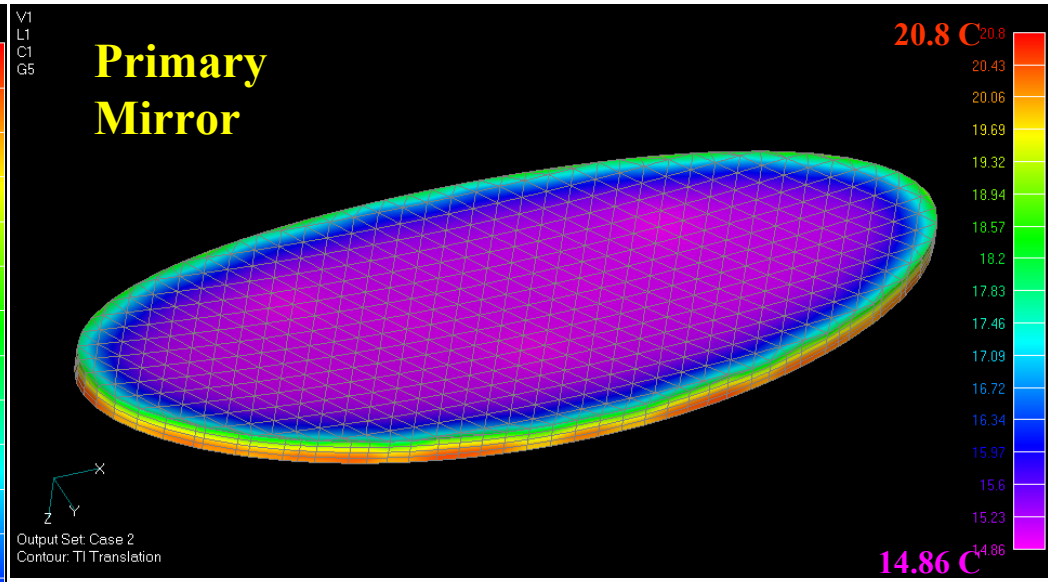
	Internal Enclosure	External Enclosure	Solution Elapsed Time	Radiation Conductor
Run #1	Diffuse(Hemicube)	Diffuse(Hemicube)	3 hr 30 min	4,718,407
Run #2	Diffuse (ec=0.05)	Specular (ec=0.05)	2 days 23 hr 58 min	7,320,528
Run #3	Diffuse (ec=0.02)	Specular (ec=0.02)	6 days 7 hr 57 min	8,086,053

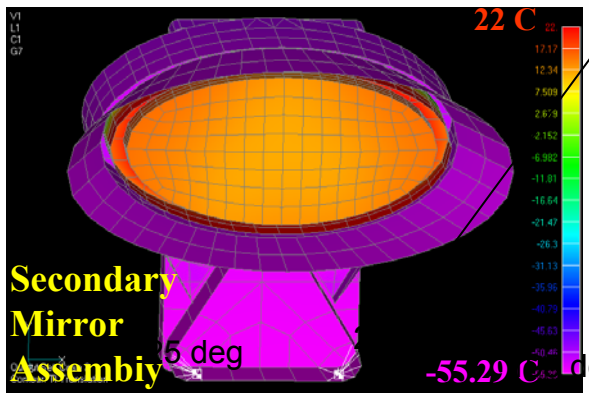
* Old Thermal Community Workstation: Dell Precision Work station 530 (2.2 Ghz)
  TMG: Version 11.0.321

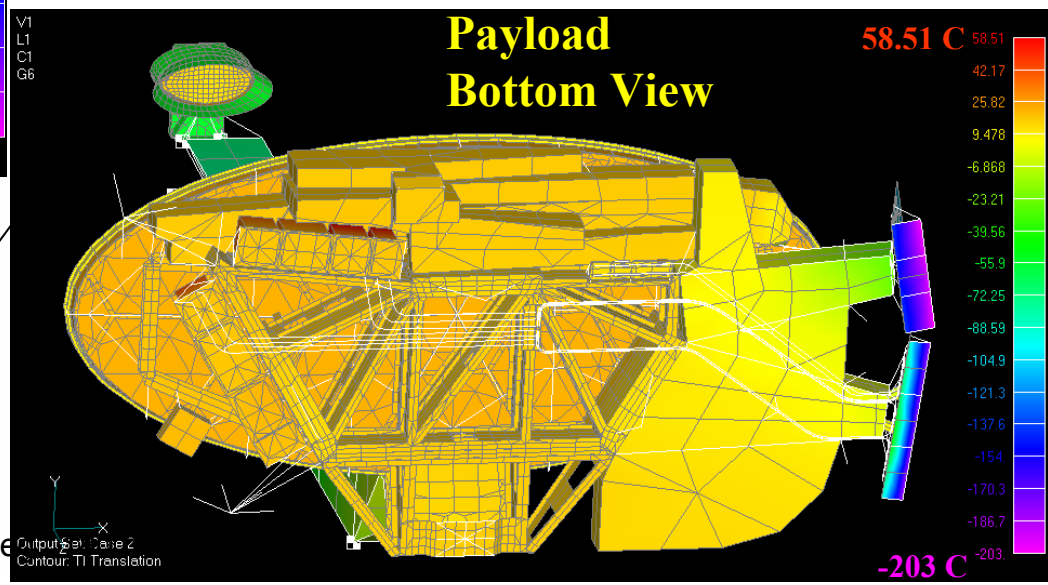
* New Thermal Community Workstation: Dell Precision Work station 670 (3.6 Ghz)
  TMG: Version 11.0.684
  Solution Elapsed Time for Run#3: 3days 19 hours

Temperatures for 195deg Sun Angle

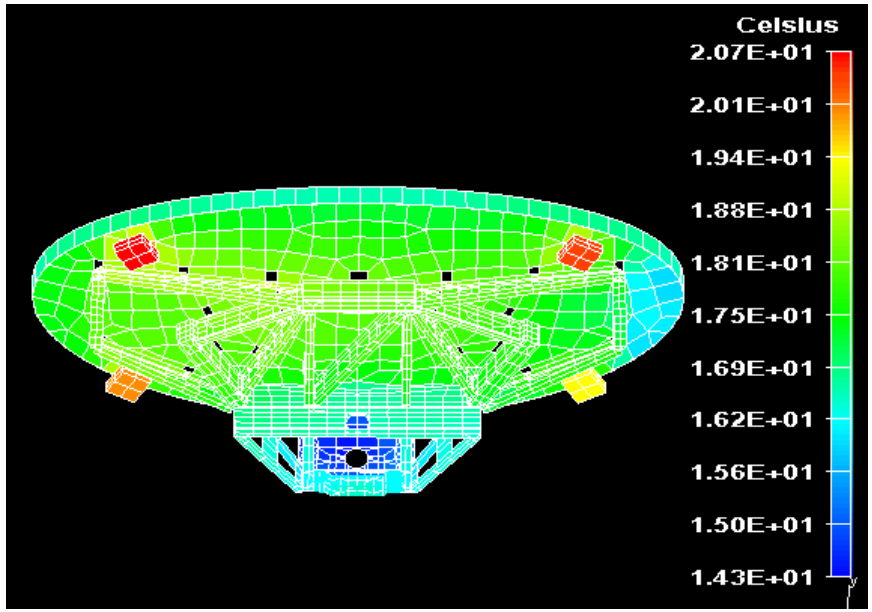




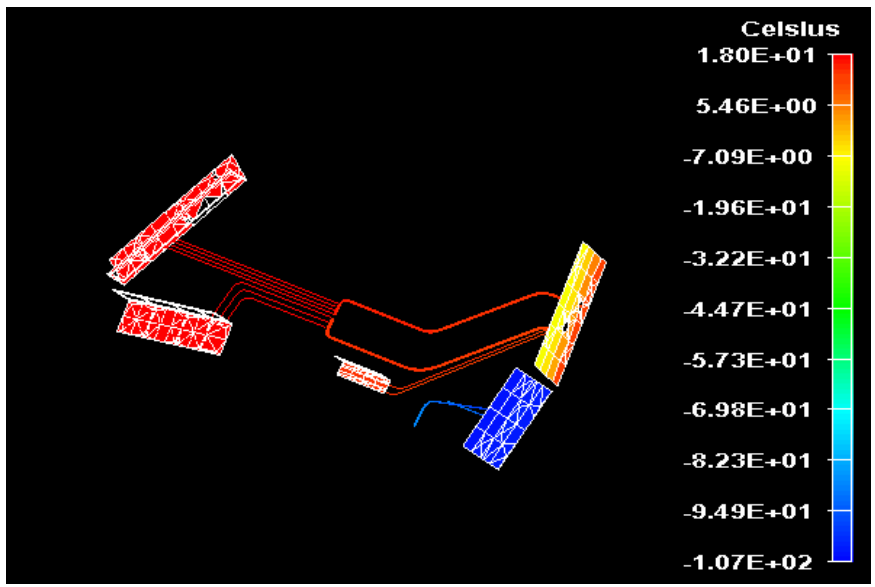




Temperatures for 195deg Sun Angle

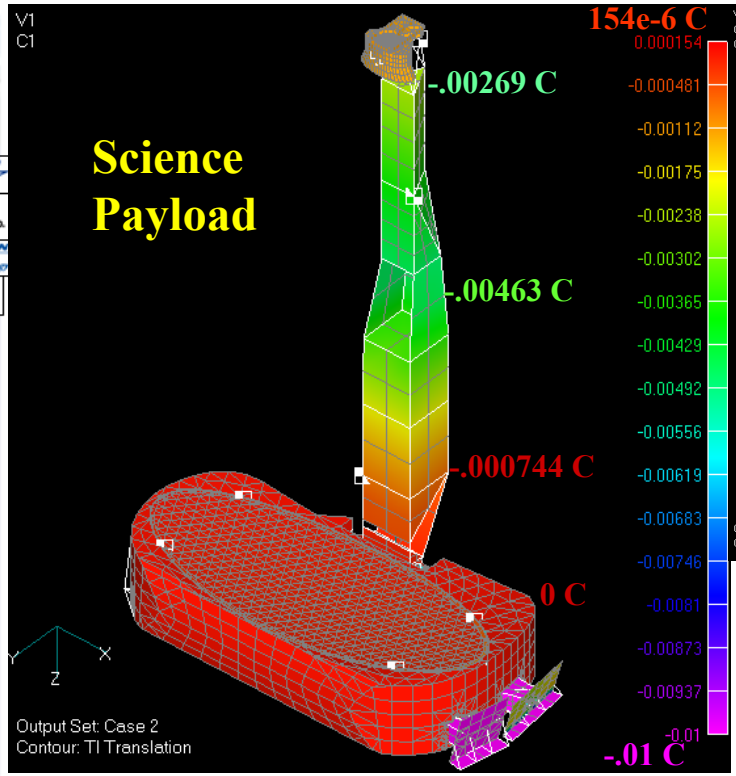


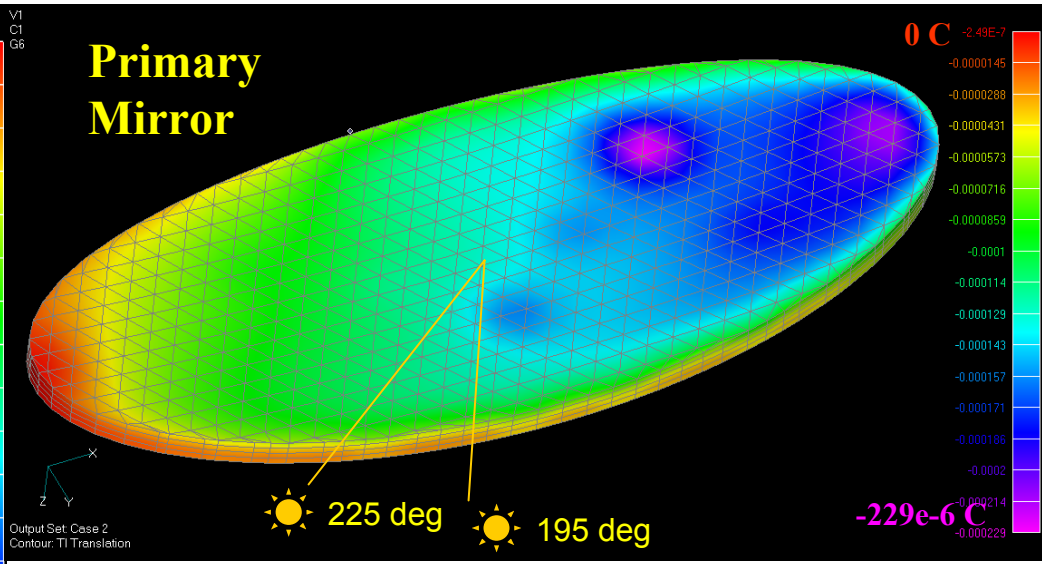
Temperatures of OTA laser electronics are from 19 to 21°C only by radiative cooling from chasses

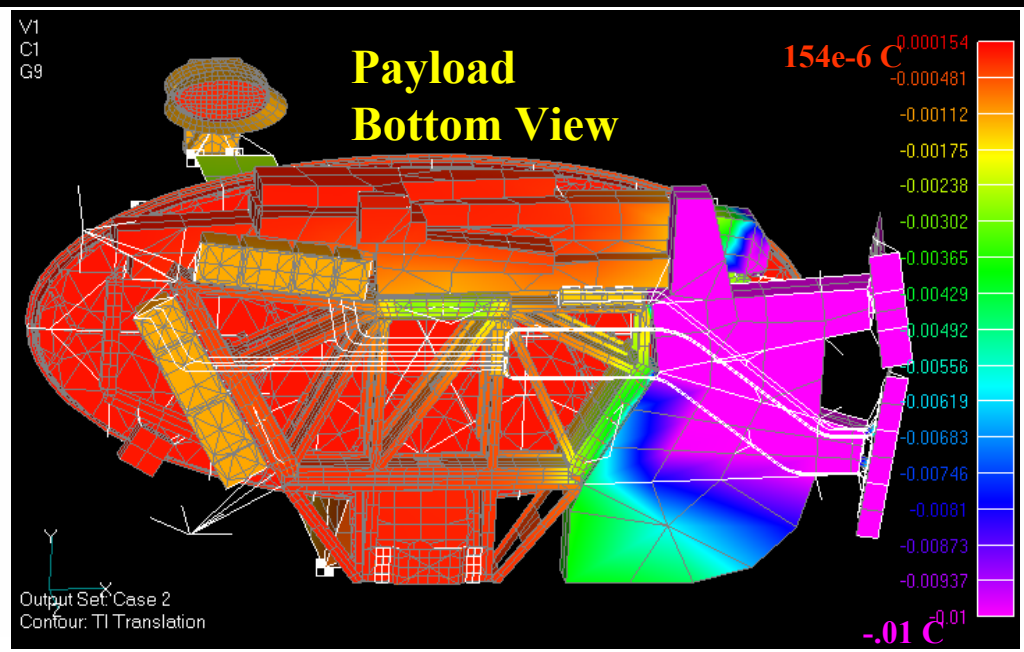


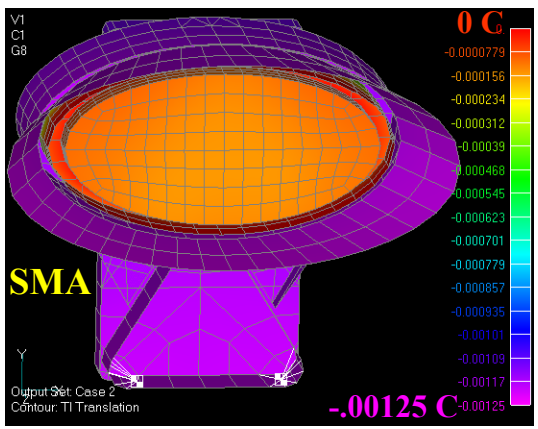
Most PSA electronic mounting plate temperatures are maintained below 18°C by combination of heat pipes and a radiator

Delta-Temps for 30 deg Dither (Steady-State, 195-225 deg): Hemi-Hemi





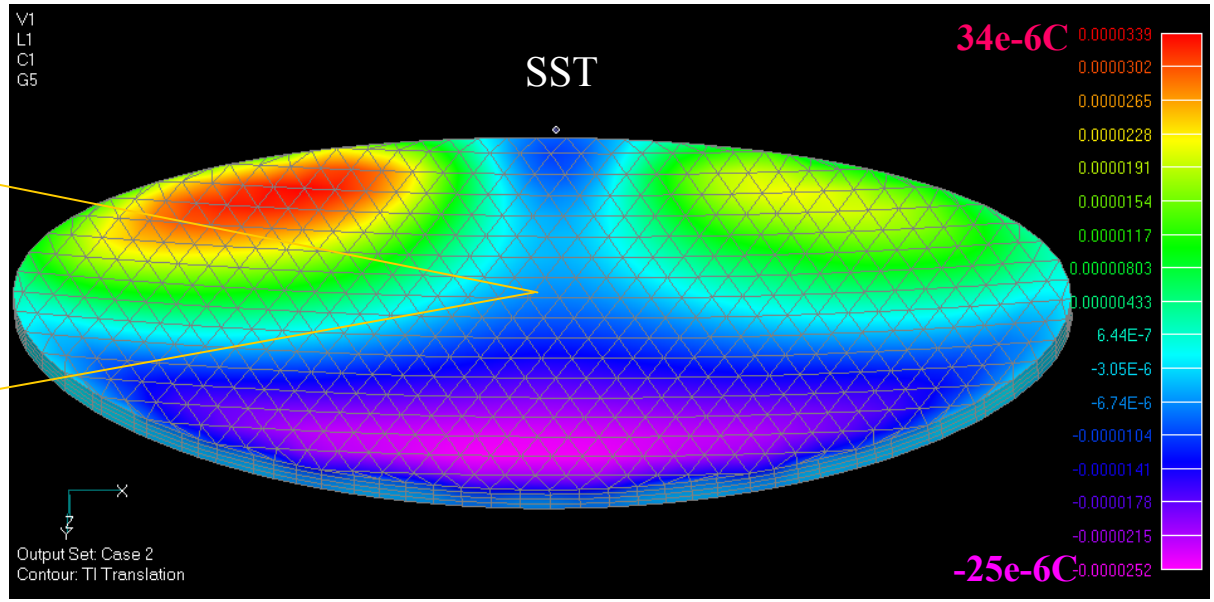




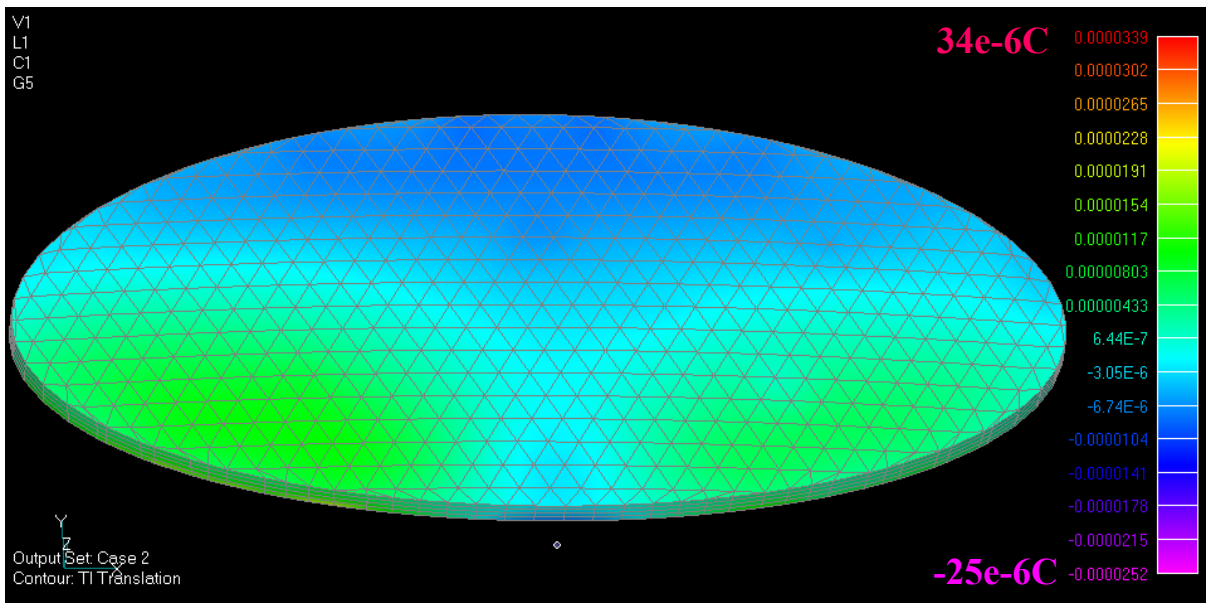
Delta-Temps for 30 deg Dither (Steady-State, 255-285 deg): Hemi-Hemi

285 deg

255 deg

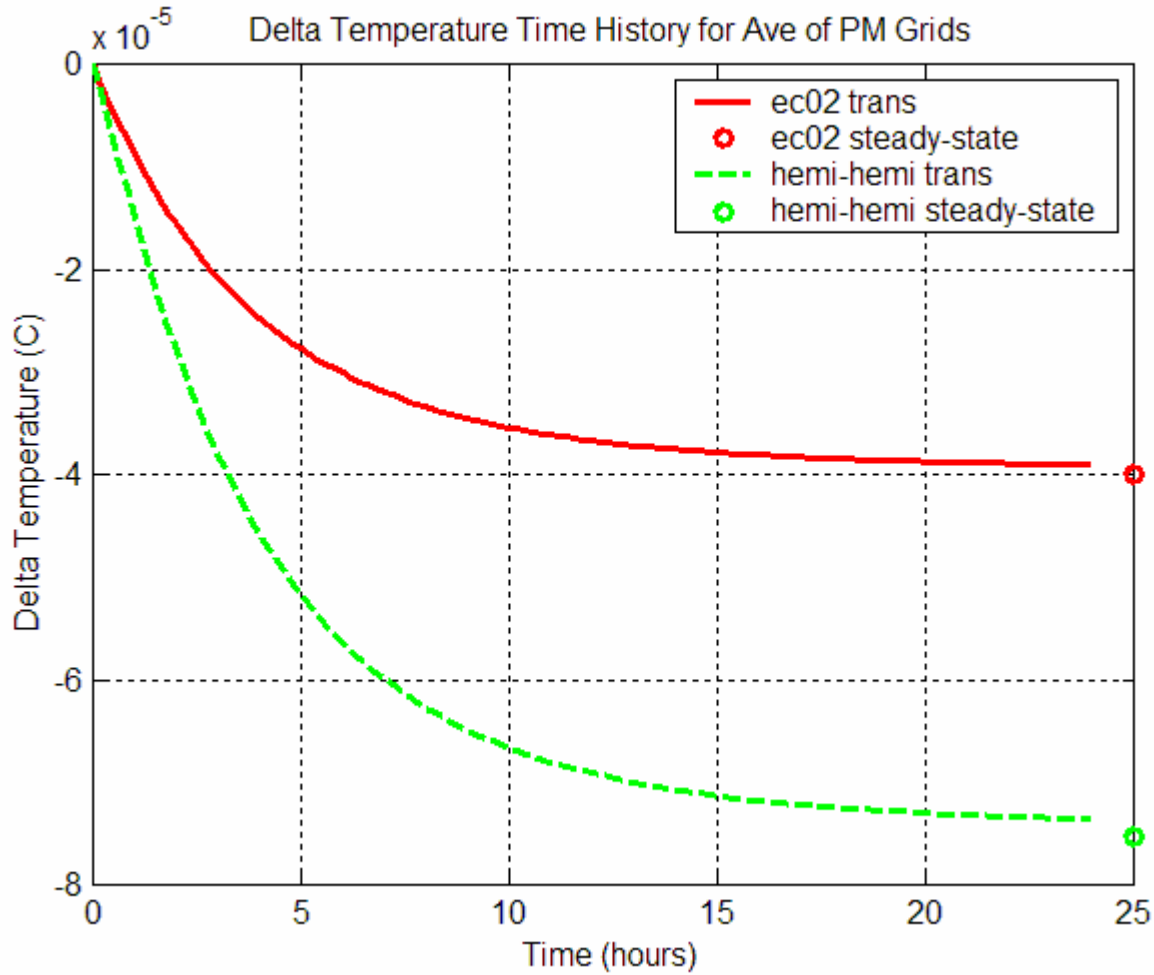


PM front



PM back

Delta-Temp Time-History: Averaged Temp of PM 30 deg Dither (195 to 225 deg)

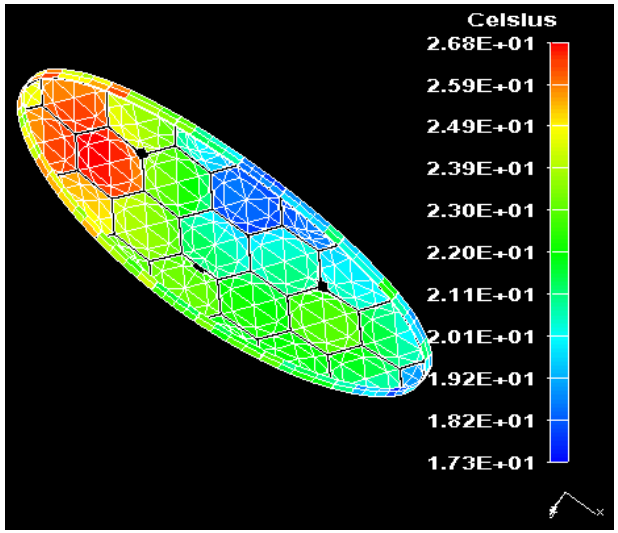


Temperature Control Heater Powers
255 deg Sun Angle

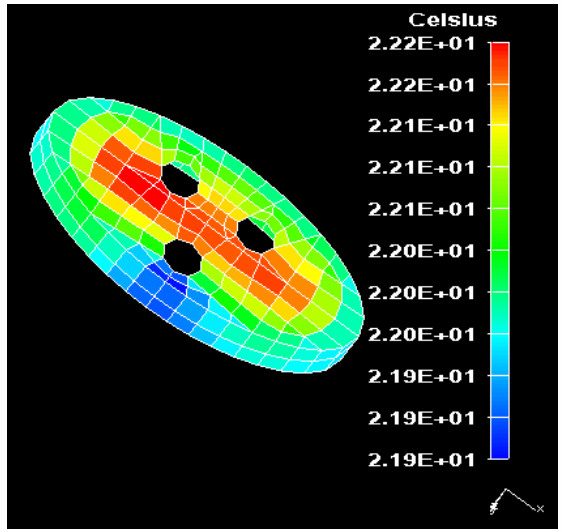
Heaters	Set Temp, ^{o}C	power*, w
PM Bot Heaters	22	336.78
PM Side Heaters	22	389.69
SM Top Heaters	22	14.29
SM Side Heaters	22	17.25
M3 Back heaters	22	0.88
Thermal Enclosure Heaters	17	622.29
SST Mounting Heaters	17	13.60
Total		1394.78

* powers required to maintain heaters at set temperatures

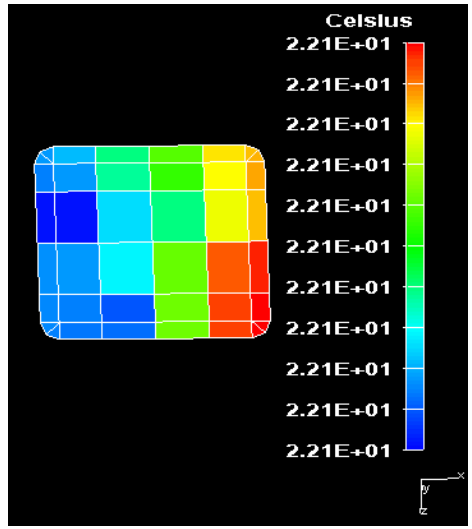
Heater Temperatures with constant powers 255 deg Sun Angle



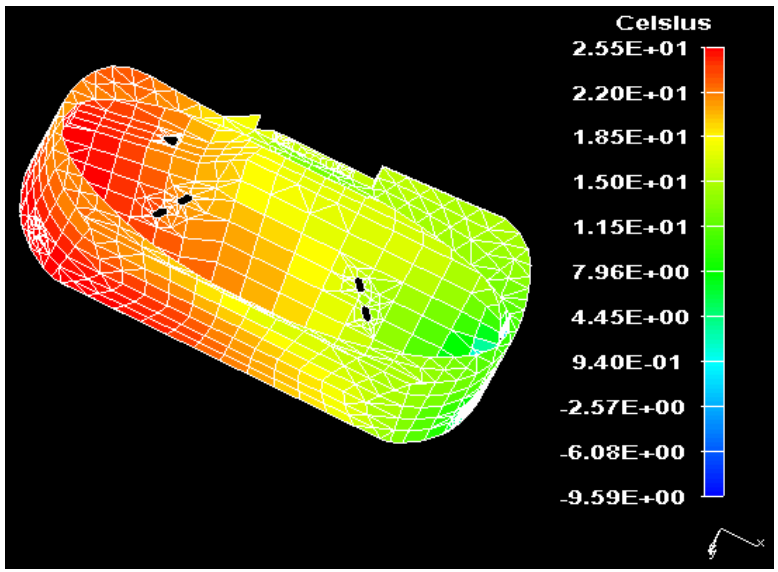
Primary Mirror Heaters



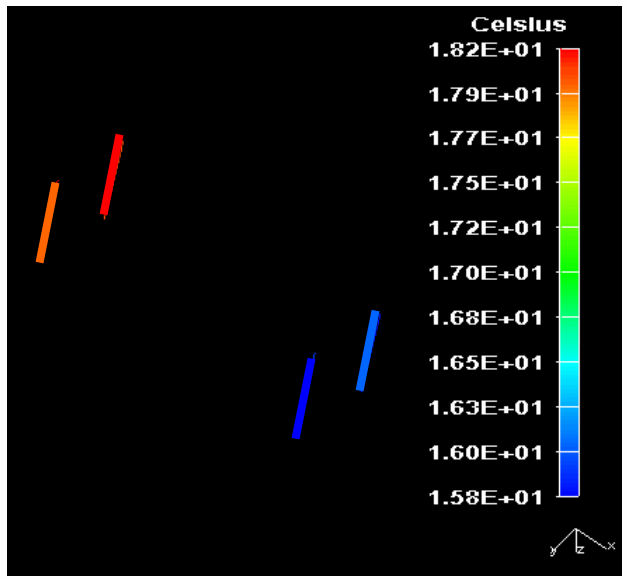
Secondary Mirror Heaters



Tertiary Mirror Heaters



Thermal Enclosure Heaters



SST Mounting Beam Heaters

Wrap-Up

Conclusions

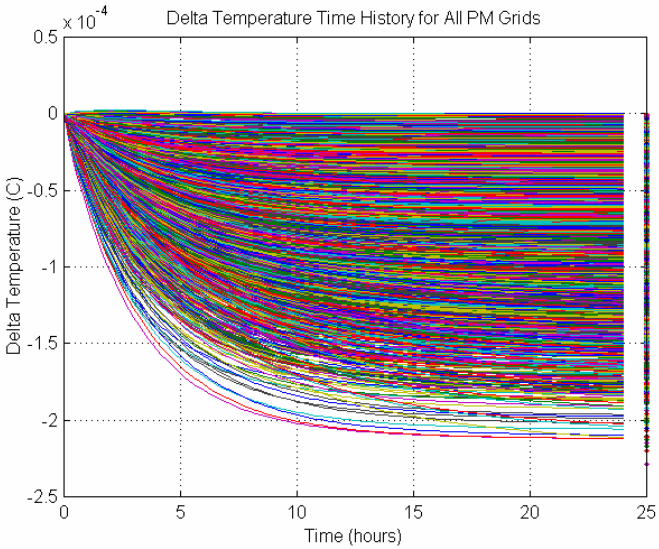
- Lessons-learned on TMG
  - Large numbers should not be used for labeling of elements: elements were relabeled using small numbers.
  - Algorithm to calculate nodal temperatures from element temperatures should be improved: nodal temperatures were recalculated by Andy using Matlab.
  - Some elements such as rigids, rods and lump masses should not be used: replaced by non-geometric elements
- Sun shield (v-grooves) works beautifully.
- Mounting plates for PSA electronics are maintained at room temp by combination of heat pipes and radiators. OTA laser electronics heat is successfully dissipated by radiation
- The 195-225 deg Dither produces much higher temperature disturbances than the 255-285 case. However, computed WFE's of the 195-225 deg Dither **with constant temp at heaters** are below requirements level.
- So far, there is no major show stopper.

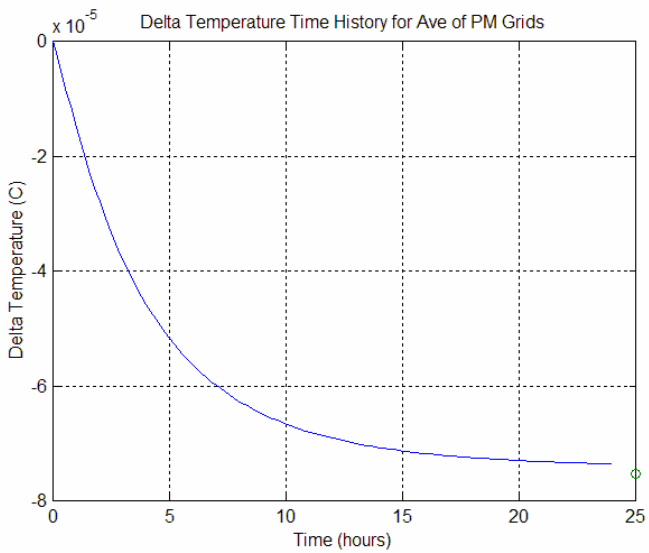
Future Studies

- Sun locations behind Telescope (including shadowing)
- Transient results with constant heater powers instead of constant heater temperatures
- Thermal optical property changes during mission
- Proceed to FB2 design and modeling

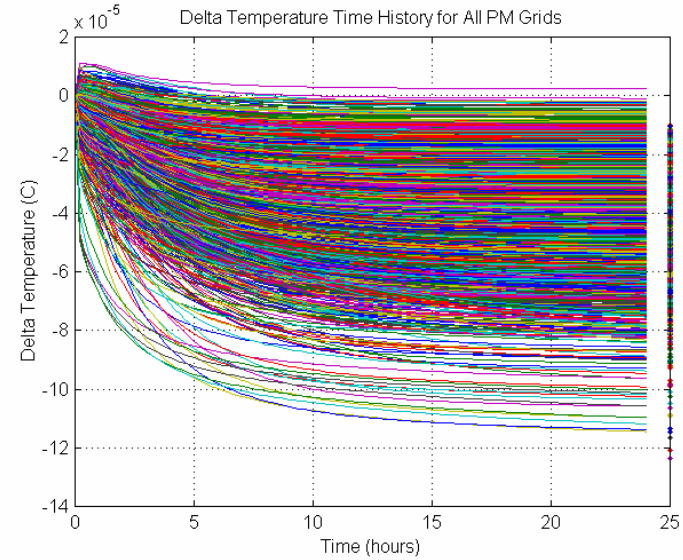
Delta-Temp Time-History
30 deg Dither (195 to 225 deg)

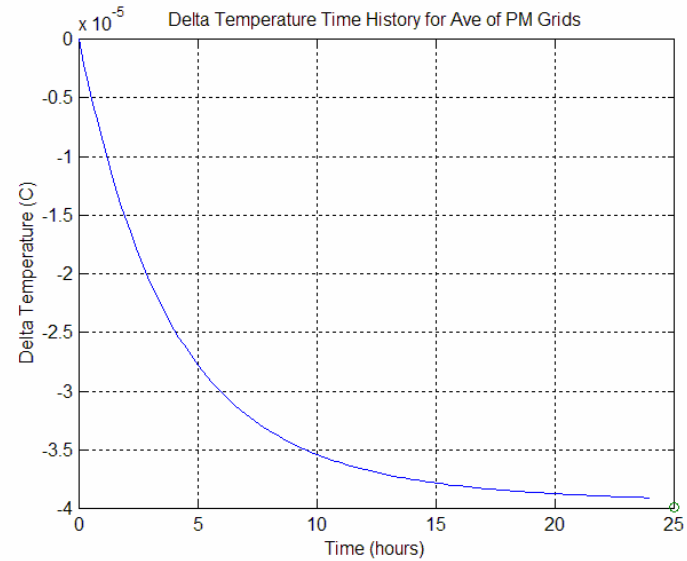
Faster "Hemi-Hemi" Method





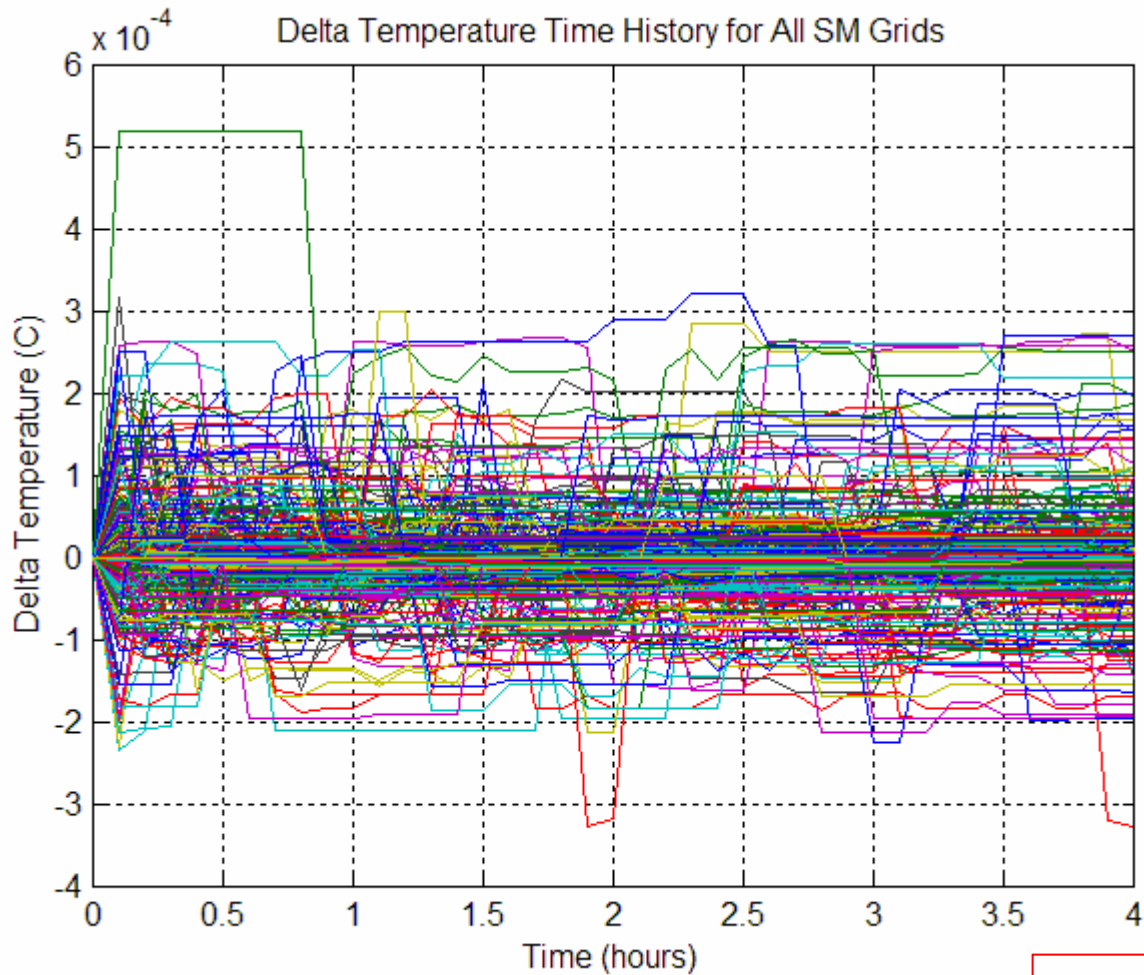
Rigorous, Slower Method (EC=0.02)





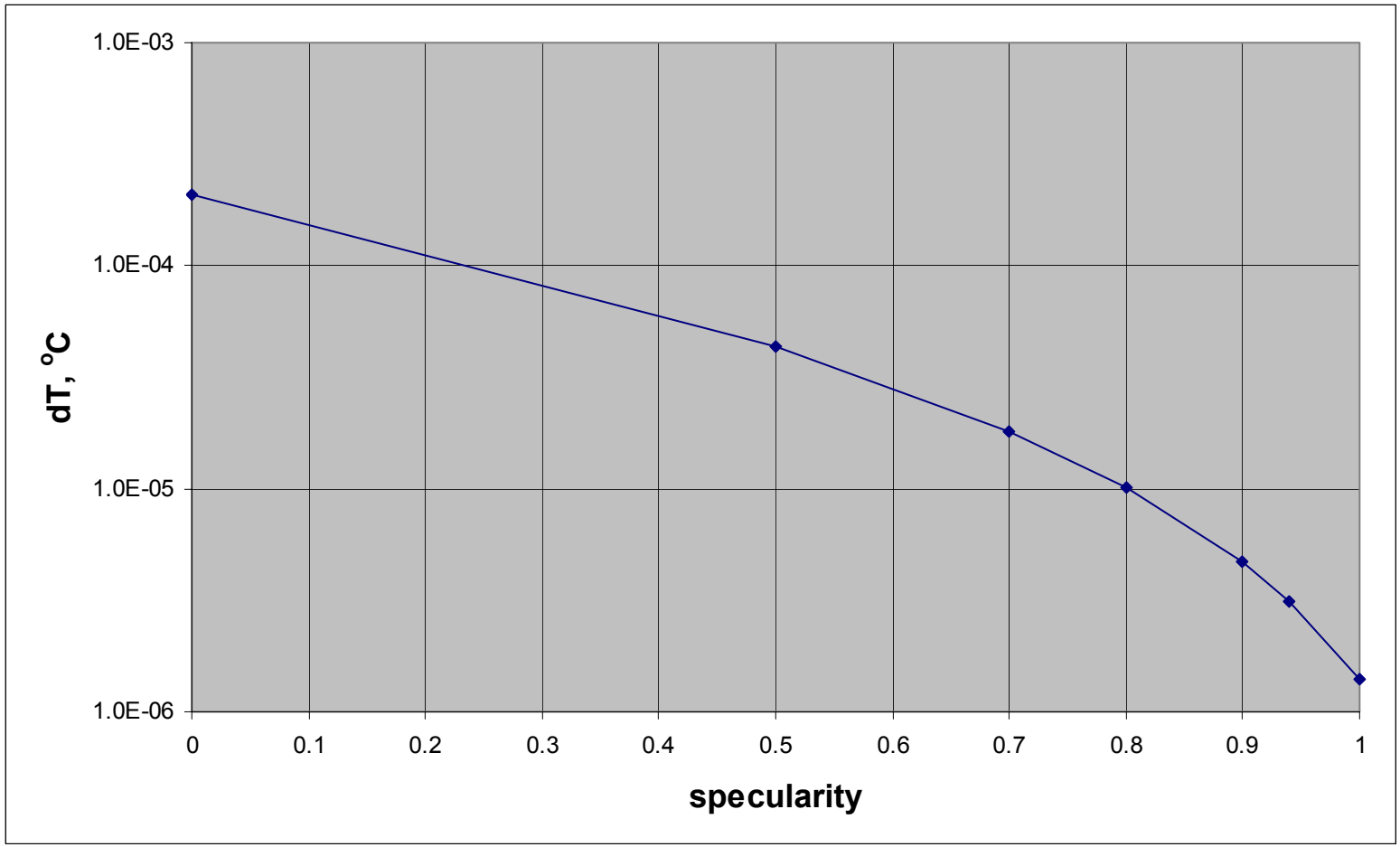
T during 30 deg. Dither from 255 to 285 deg roll

Integration control method: backward
Time step: 180 s
Convergence dT: 10^{-6}



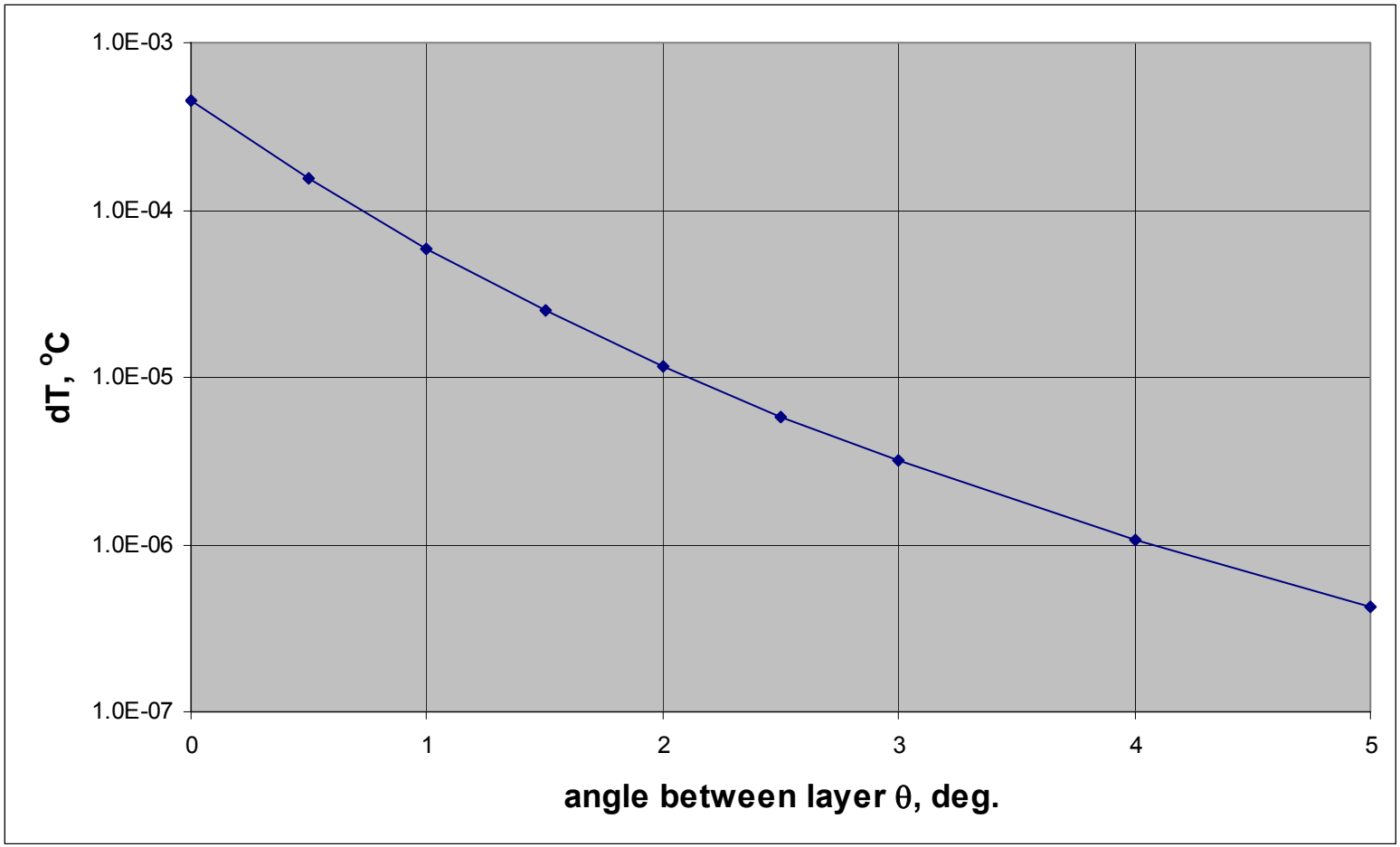
Back-Up

Maximum PM Temperature Changes during Sun moving from +Y to –Y: Specularity



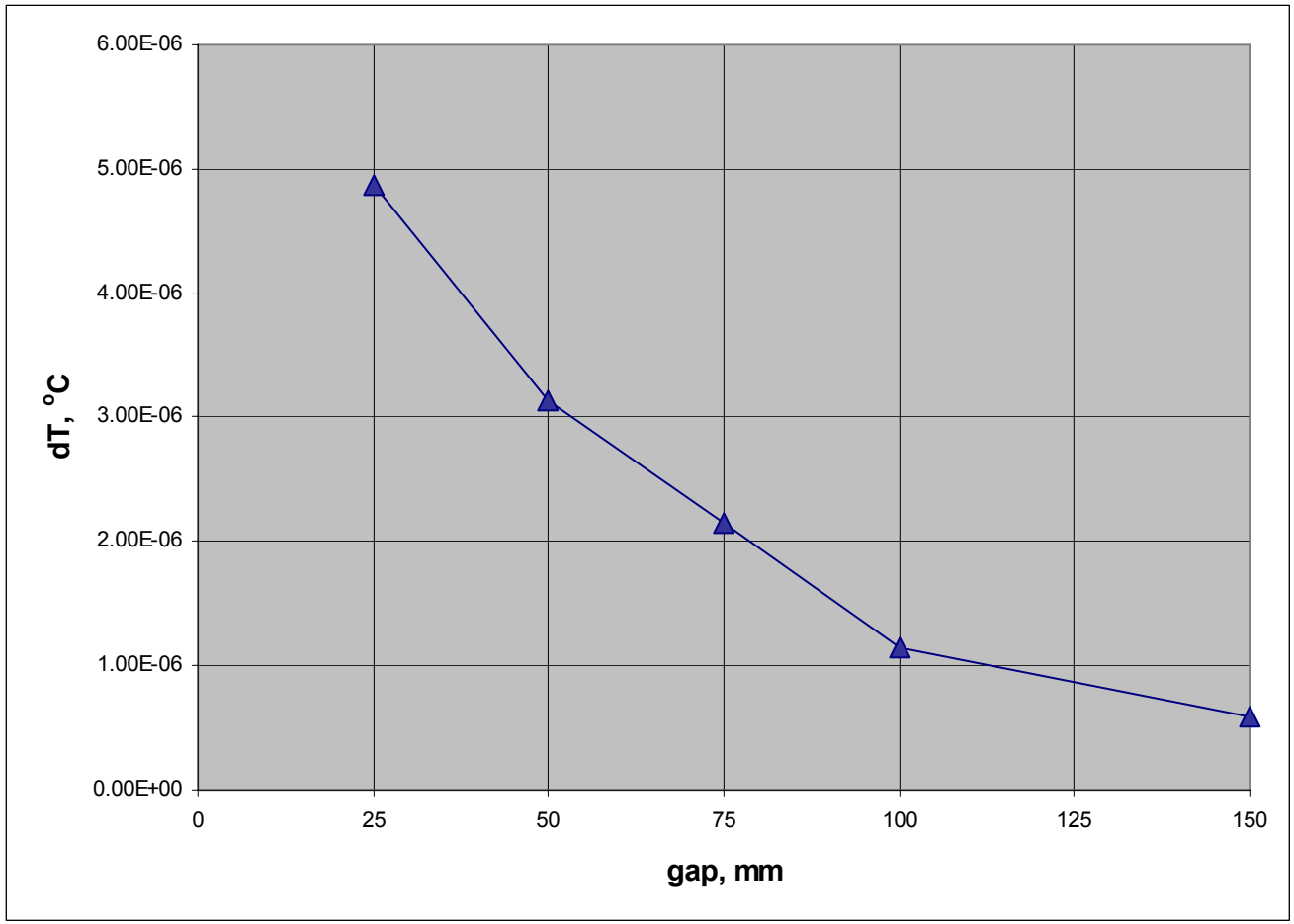
* angle between layers θ = 3deg., gap = 5 cm

Maximum PM Temperature Changes during Sun moving from +Y to –Y: Angle θ



* specularity s = 0.94, gap = 5cm

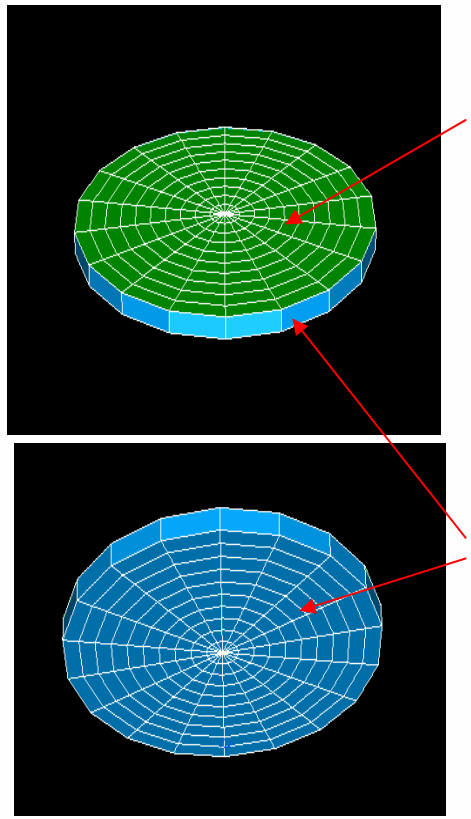
Maximum PM Temperature Changes during Sun moving from +Y to –Y: Gap



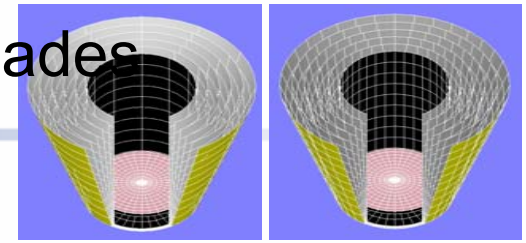
* angle between layers θ = 3deg., specularity s = 0.94

PM Temperatures with thick cylinderical TE: TMG and TSS/SINDAG

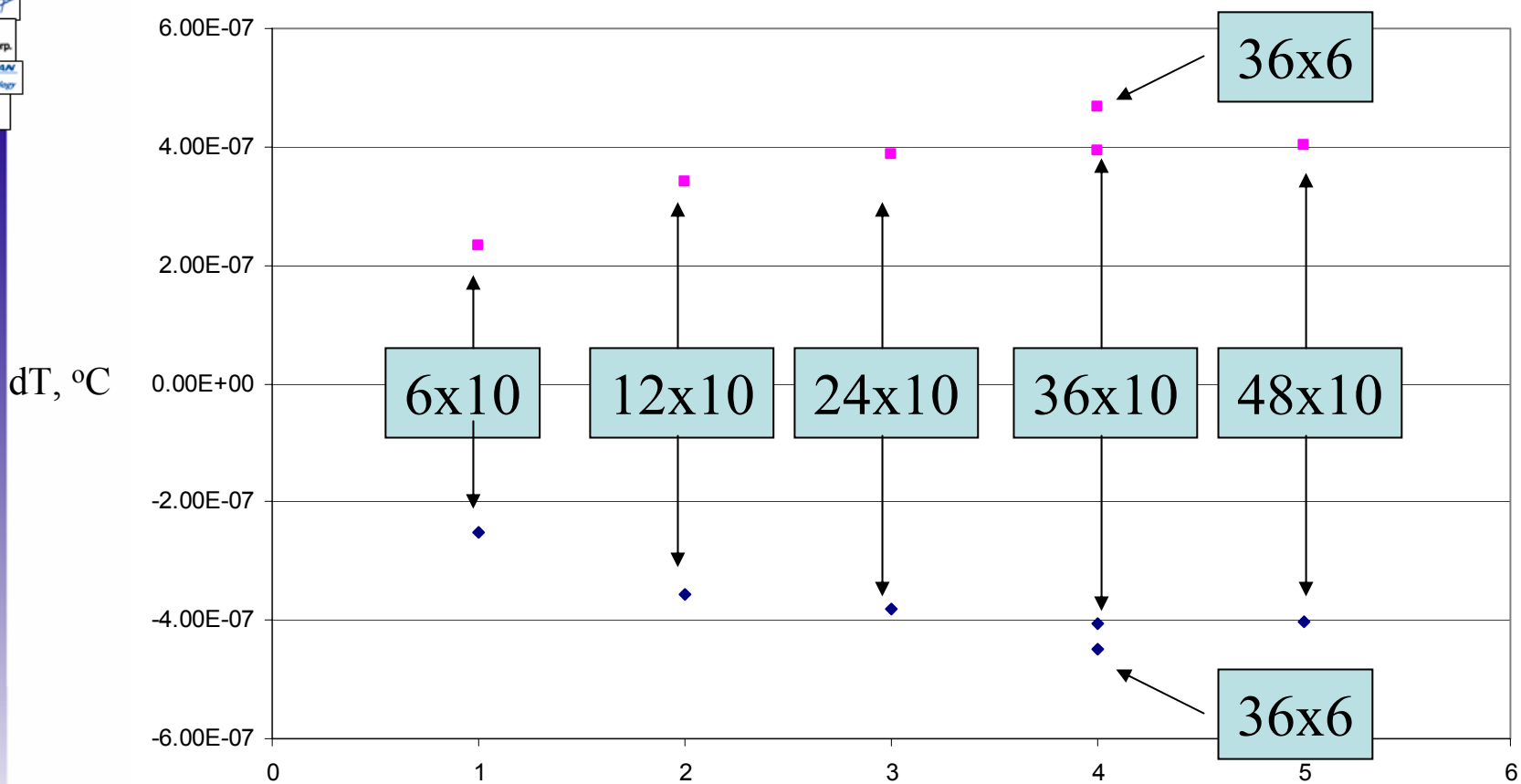
	s = 0.94 TMG	s = 0.94 TSS/SINDAG
PM avged Temp, Sun @ +X	17.363056	17.362549
PM avged Temp, Sun @ -X	17.363056	17.362549
PM min Temp, Sun @ +X	17.326949	17.327987
PM max Temp, Sun @ +X	17.480773	17.476815
PM max dT during Sun from +X to -X	-1.528E-06/ 1.526E-06	-2.710E-06/ 2.710E-06



Effects of Meshing of Sun Shades

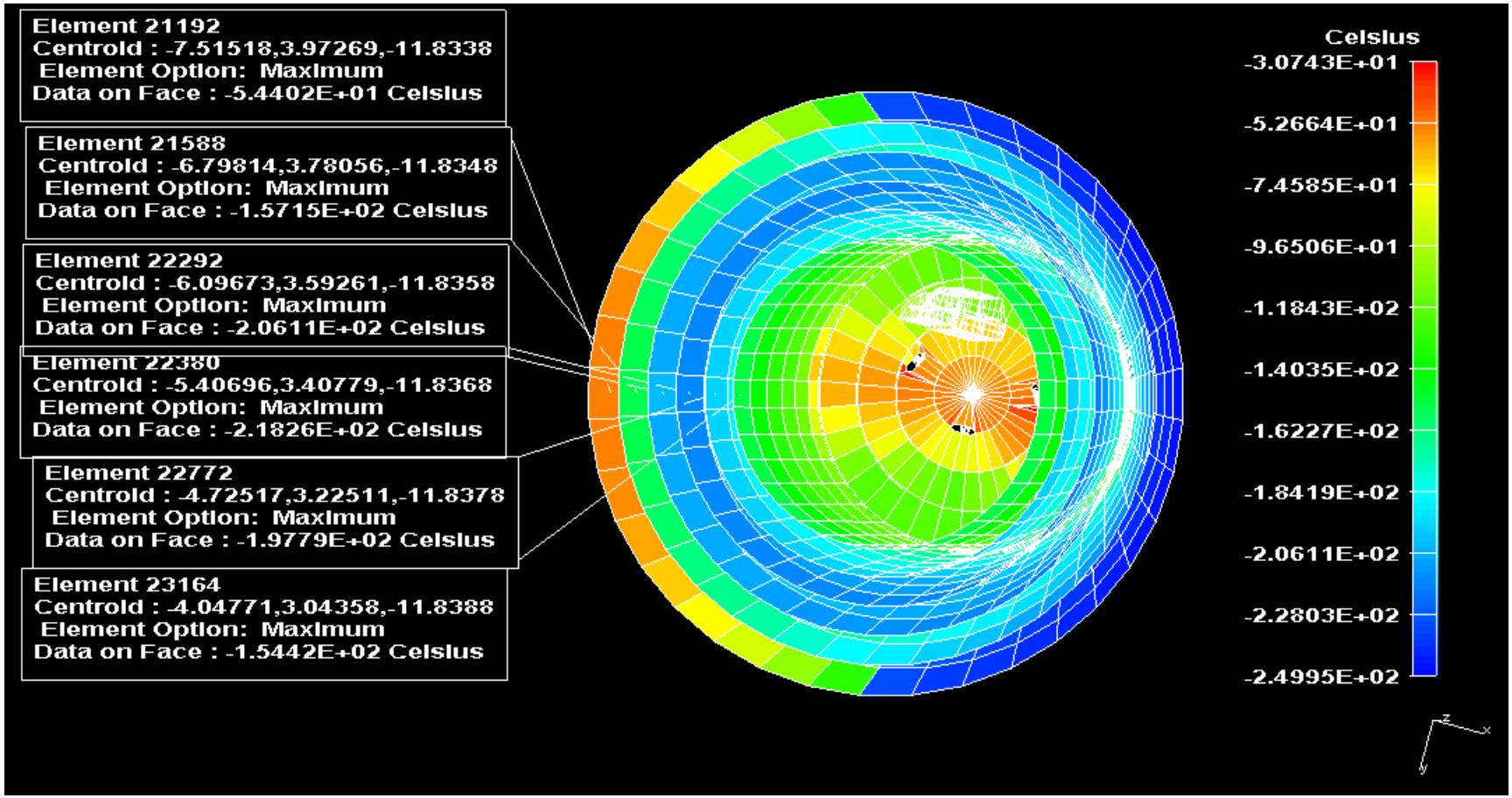


12x10 36x10



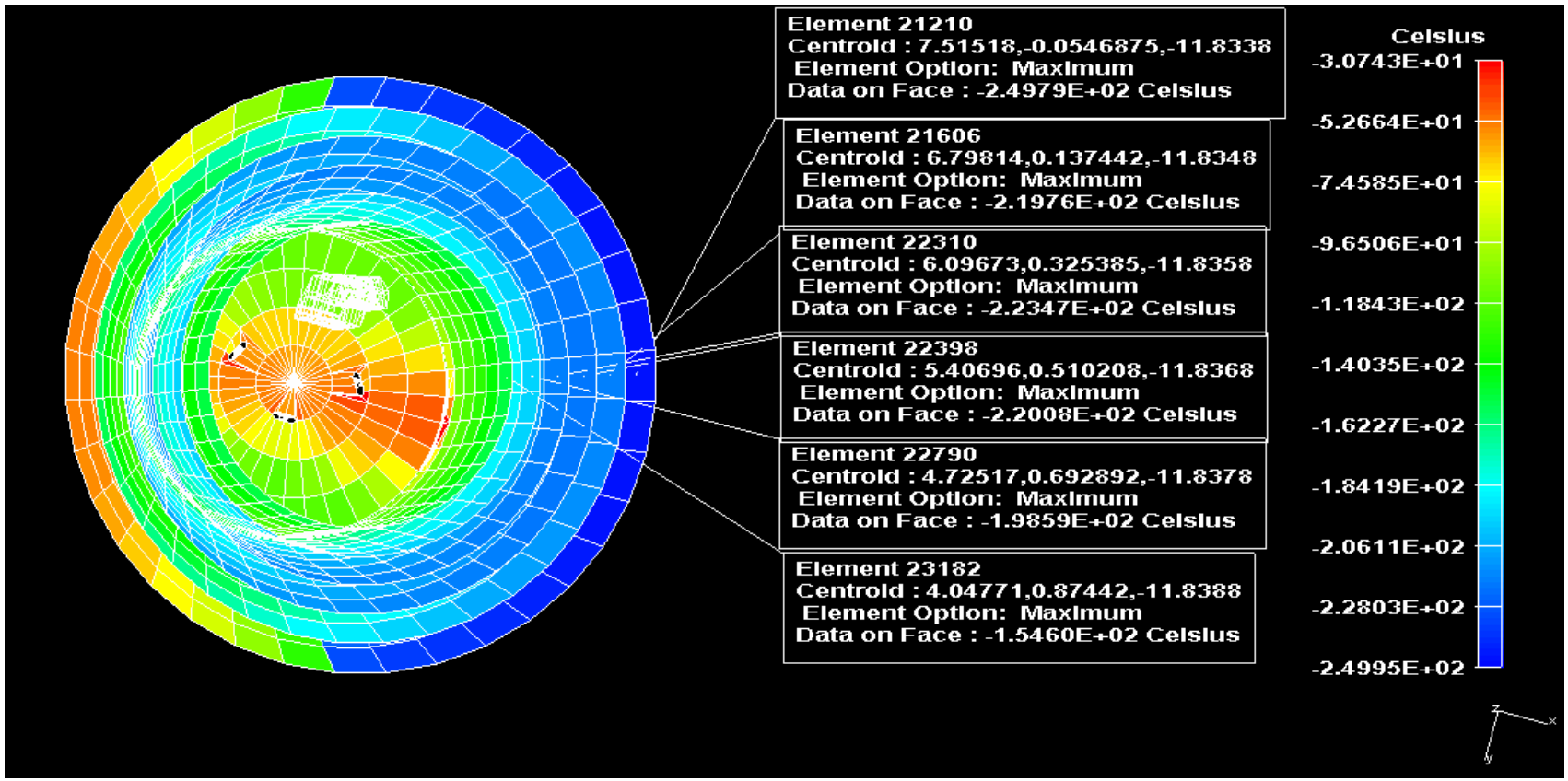
dT = max. temperature rises and drops in PM during 30 deg. dither

Sun Shield Temperatures: 255 deg roll



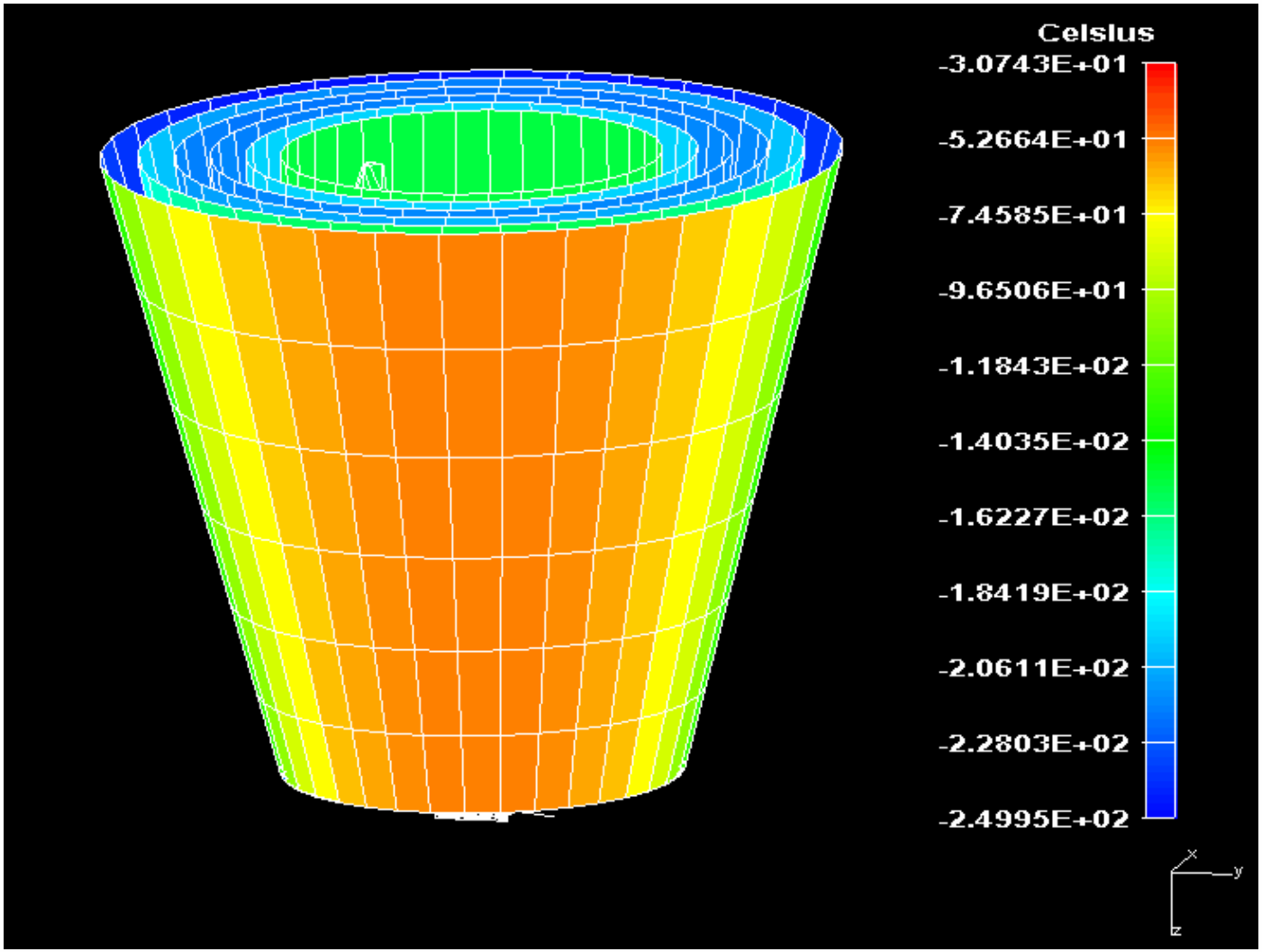
Back-Up

Sun Shield Temperatures: 255 deg roll



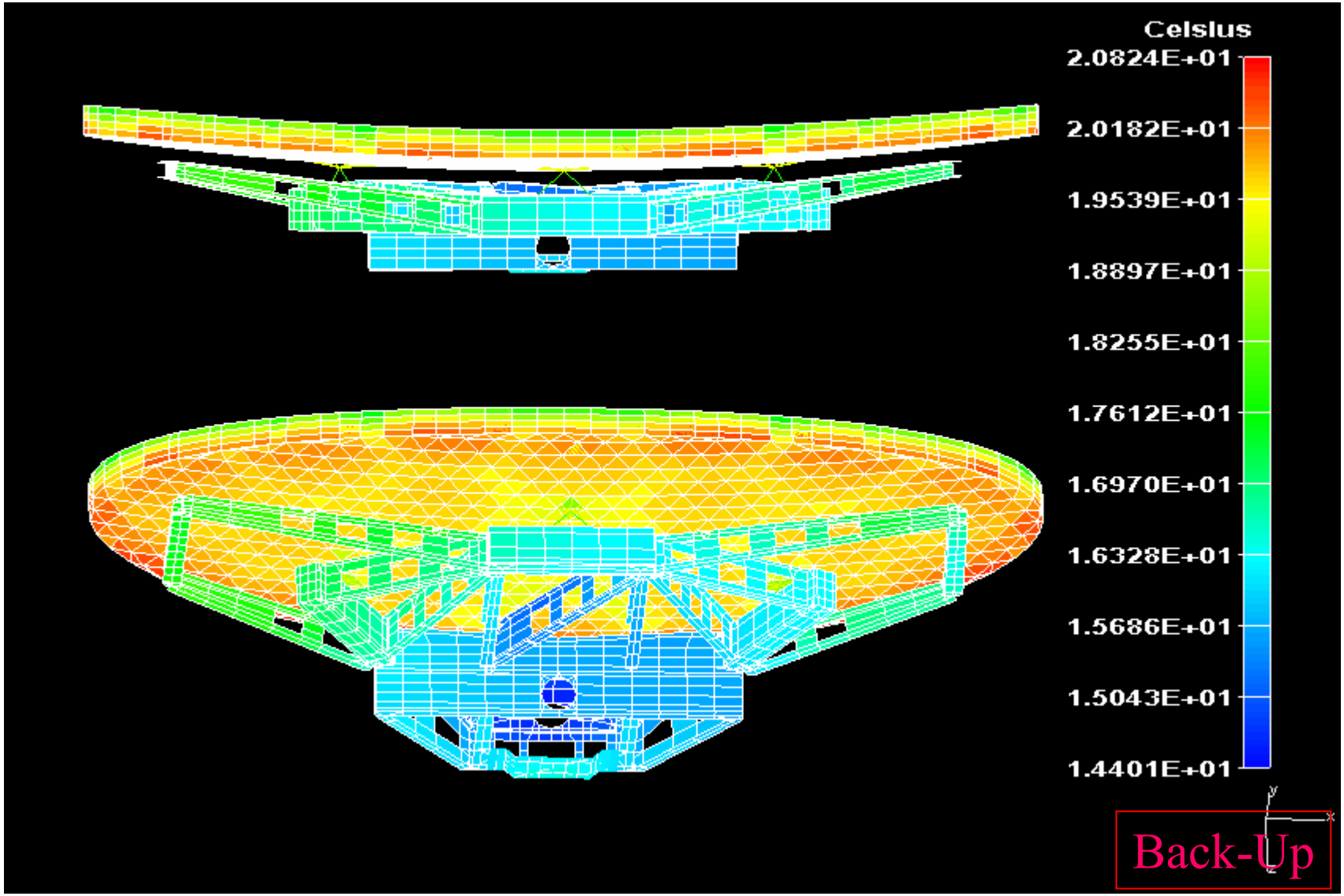
Back-Up

Sun Shield Temperatures: 255 deg roll

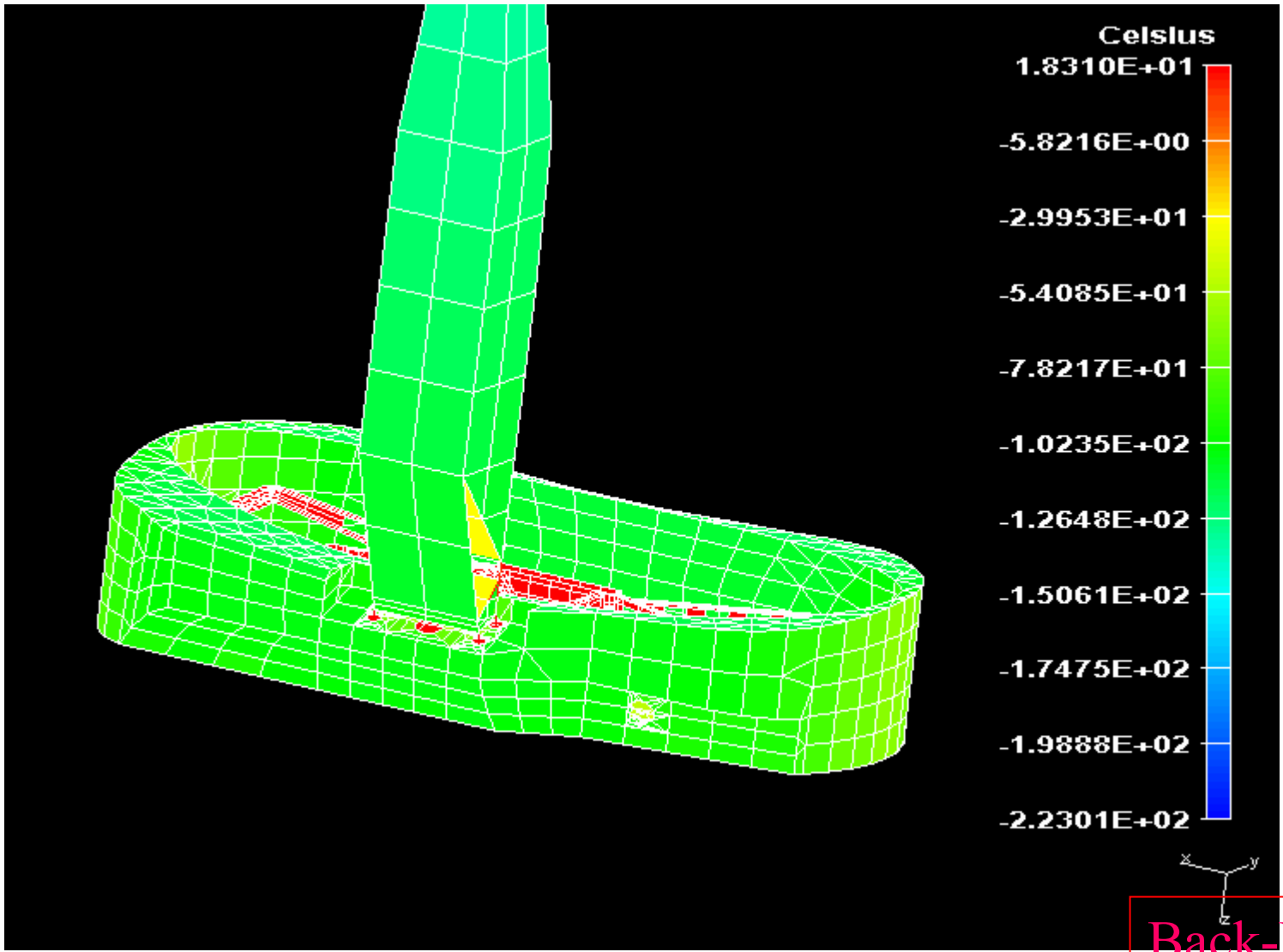


Back-Up

PM, Bipods and AMS Temperatures: 255 deg Roll

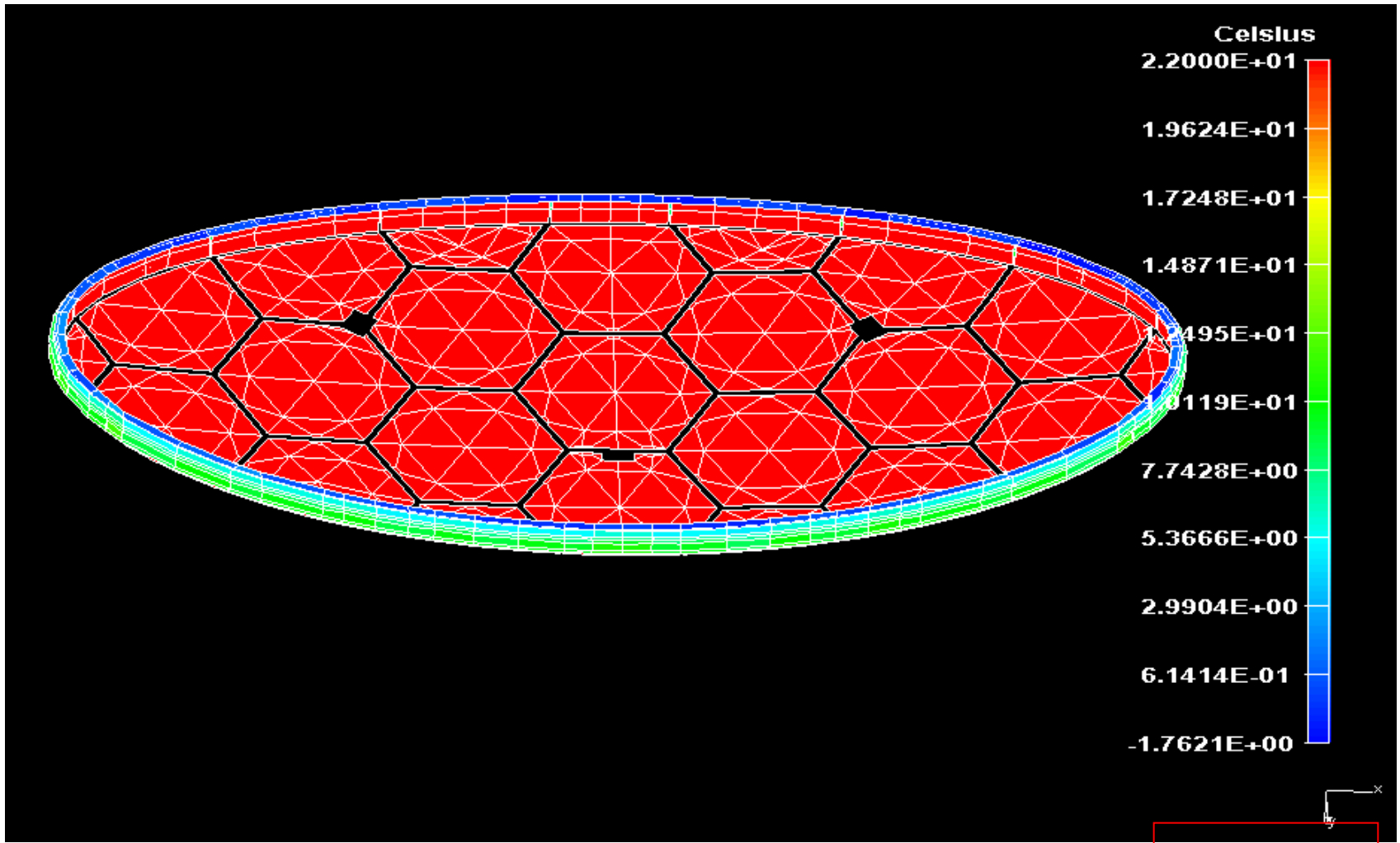


AMS View to Baffle through Holes in Thermal Enclosure



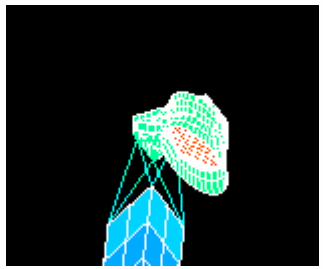
Back-Up

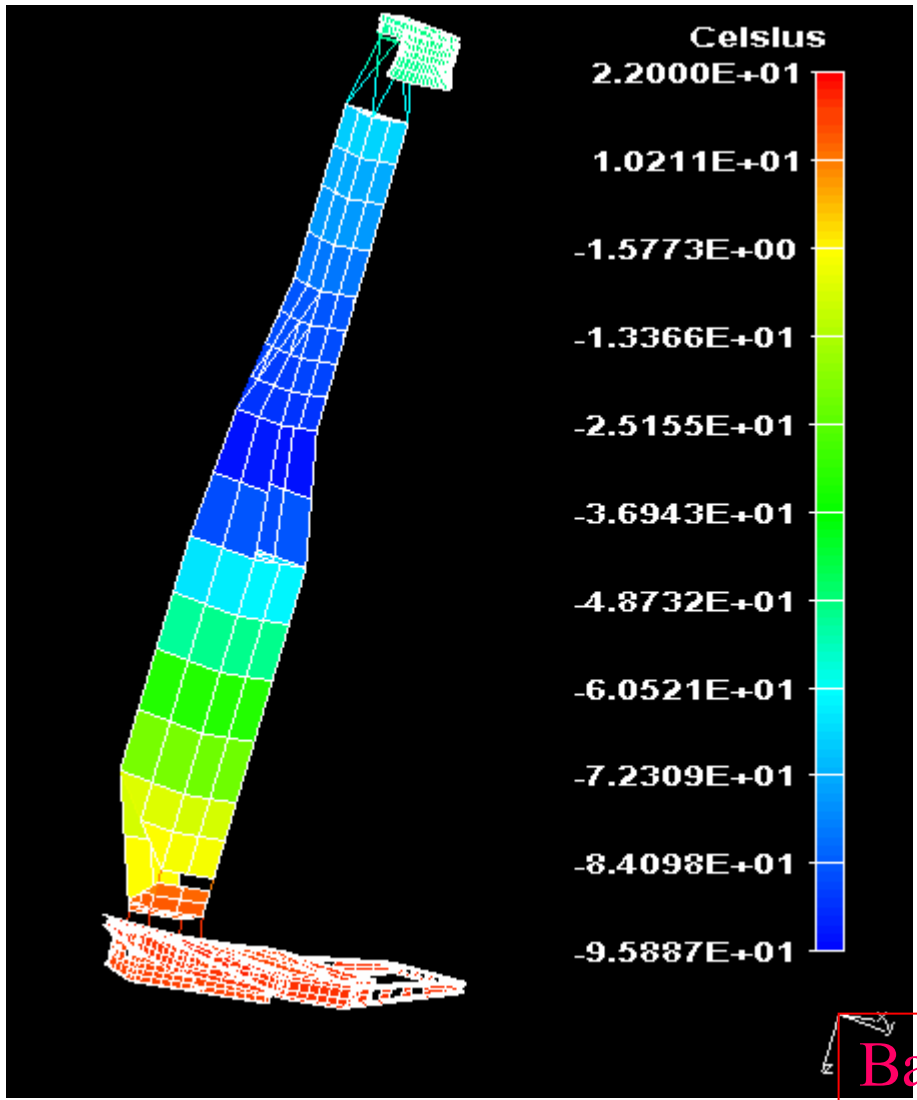
PM Heaters, Mask and C-Channel Temperatures: 255 deg Roll



Back-Up

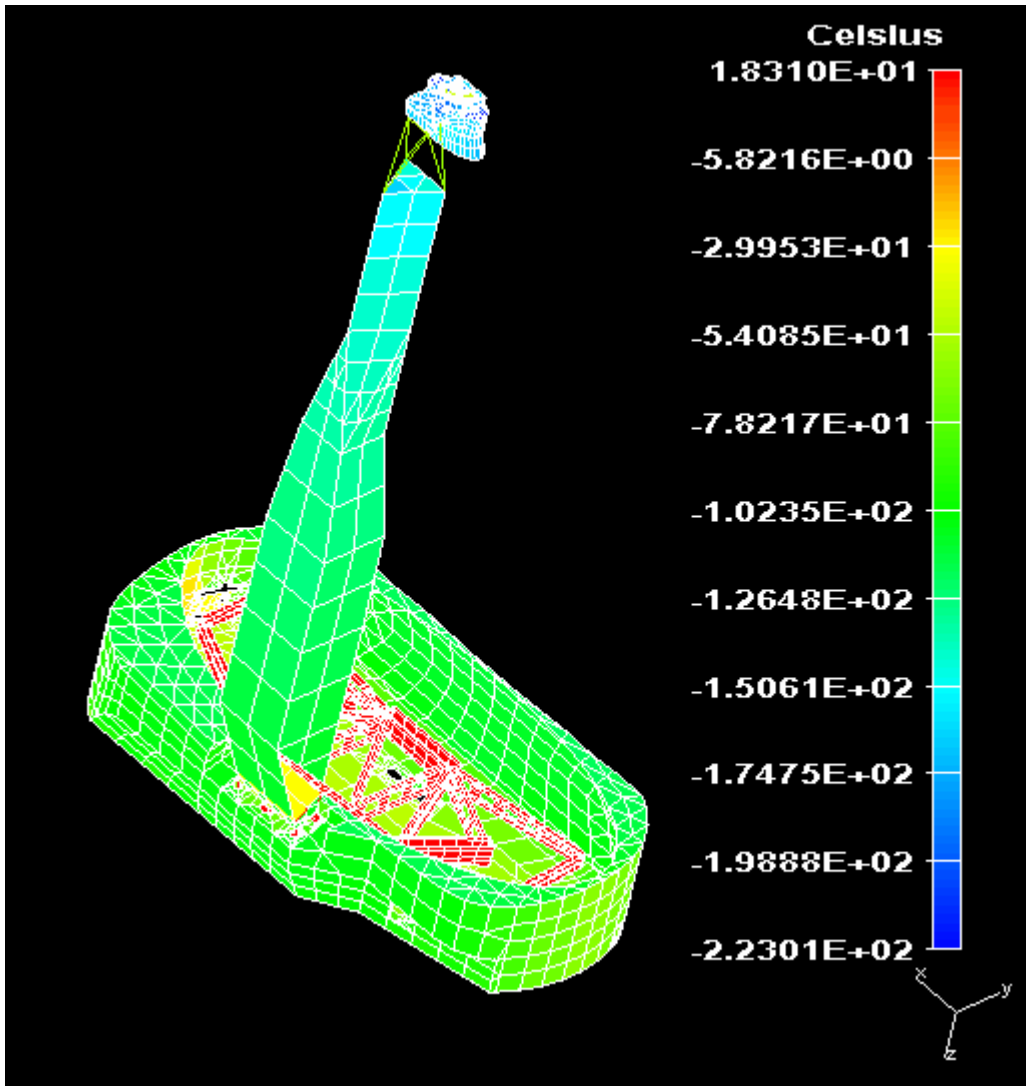
SST Temperatures: 255 deg Roll





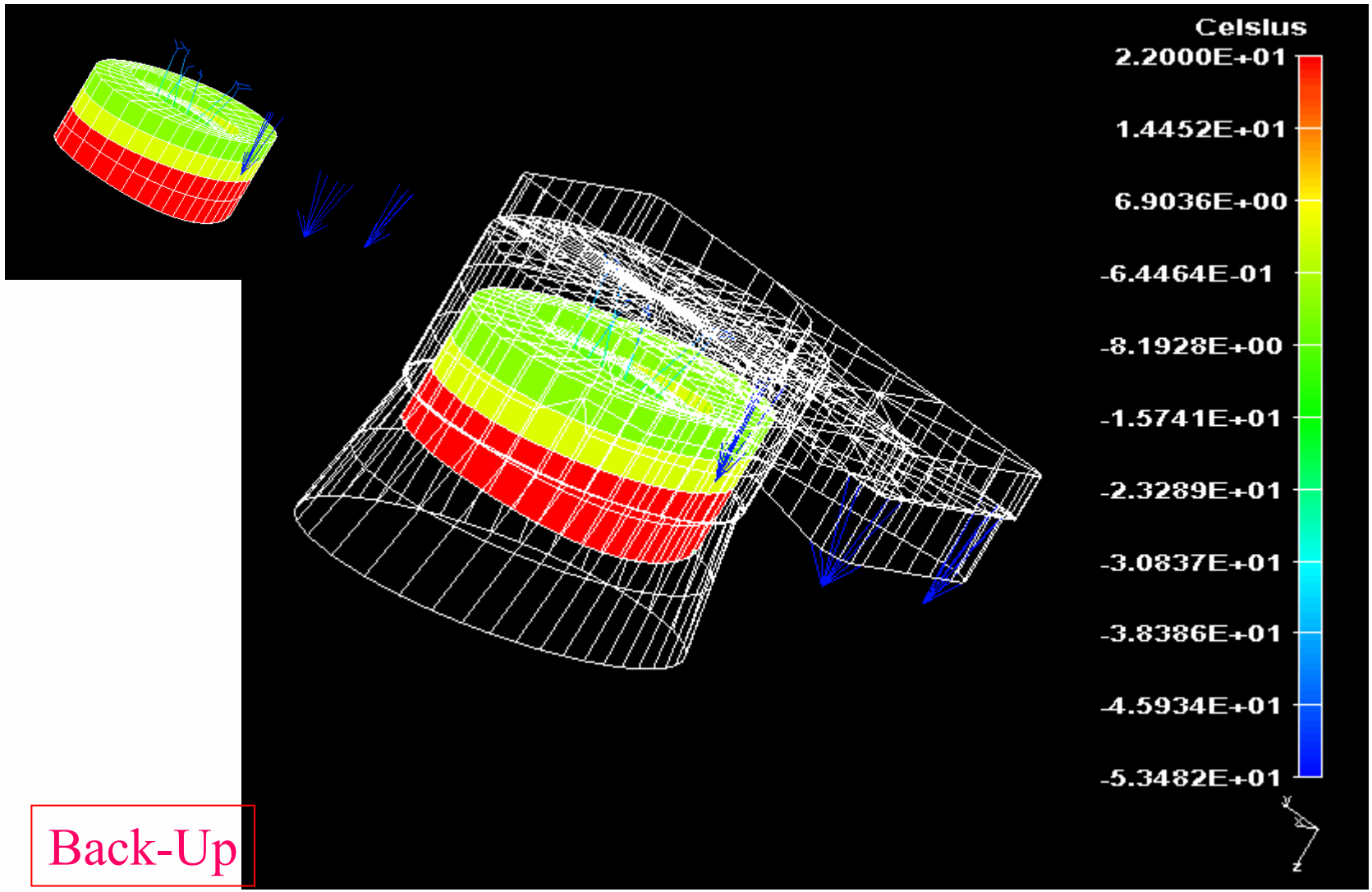
Back-Up

SMA, SST and TE MLI Temperatures: 255 deg Roll



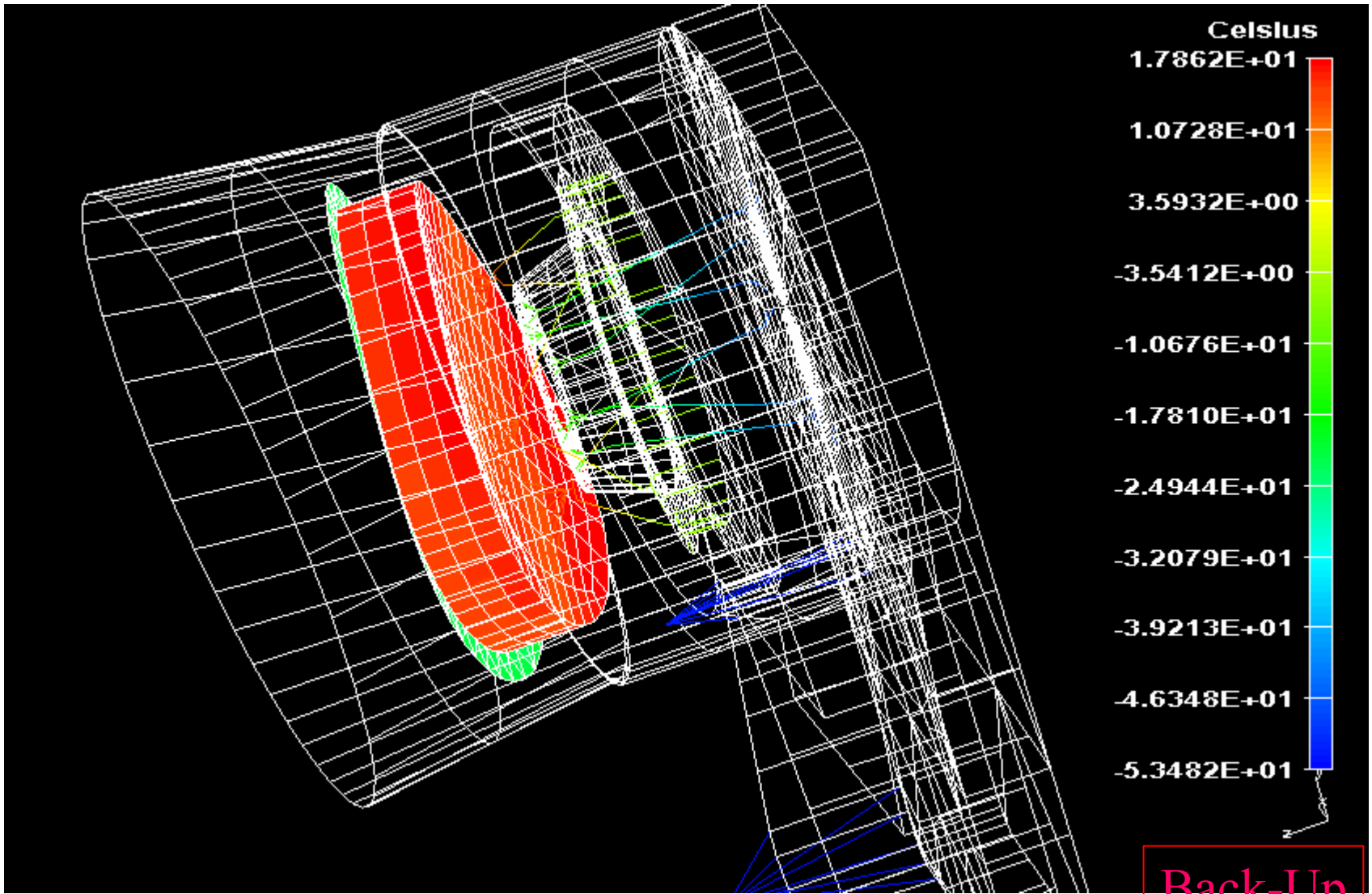
Back-Up

SMA Temperatures (outer cover removed): 255 deg Roll



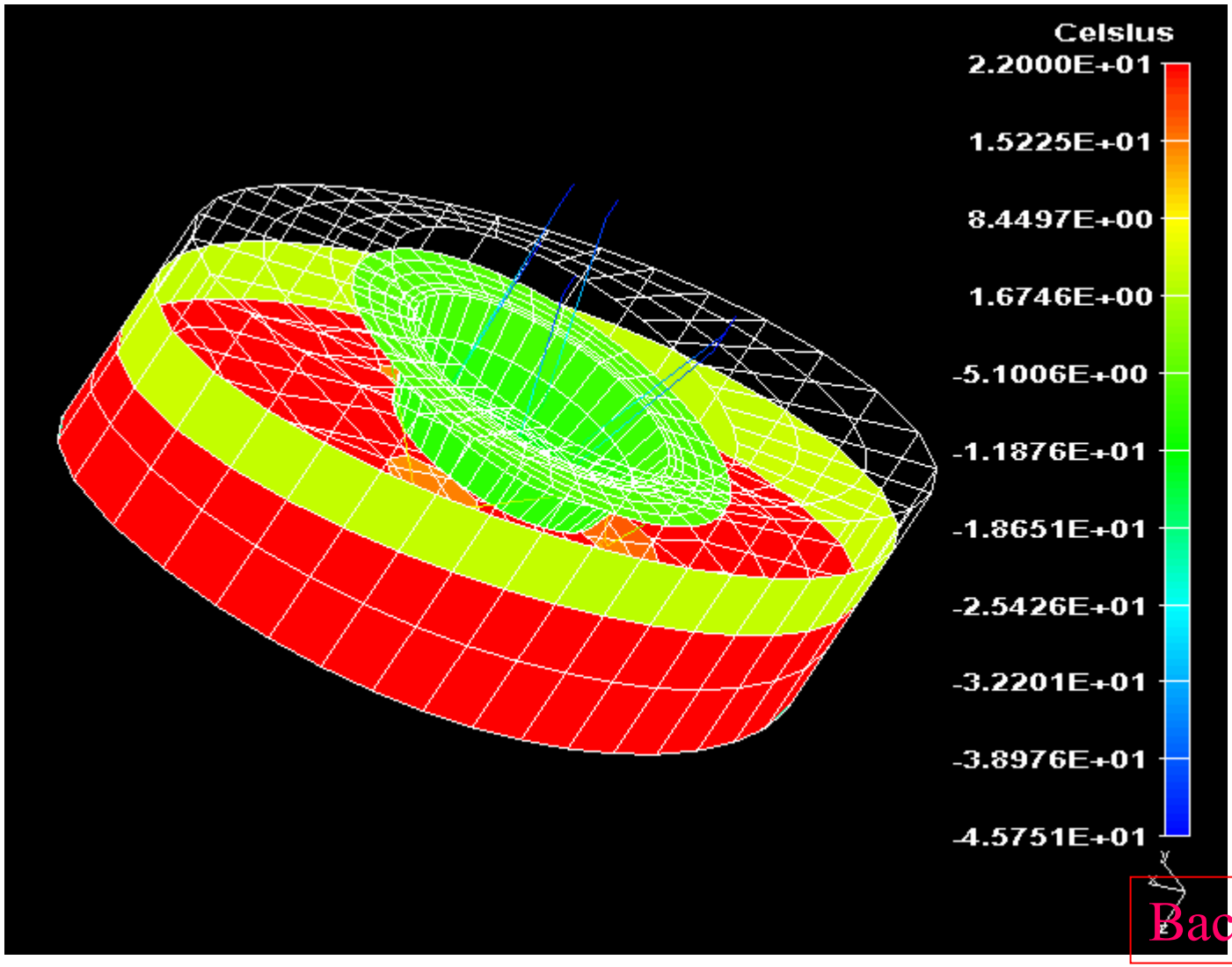
Back-Up

SMA Temperatures (outer cover removed): 255 deg Roll



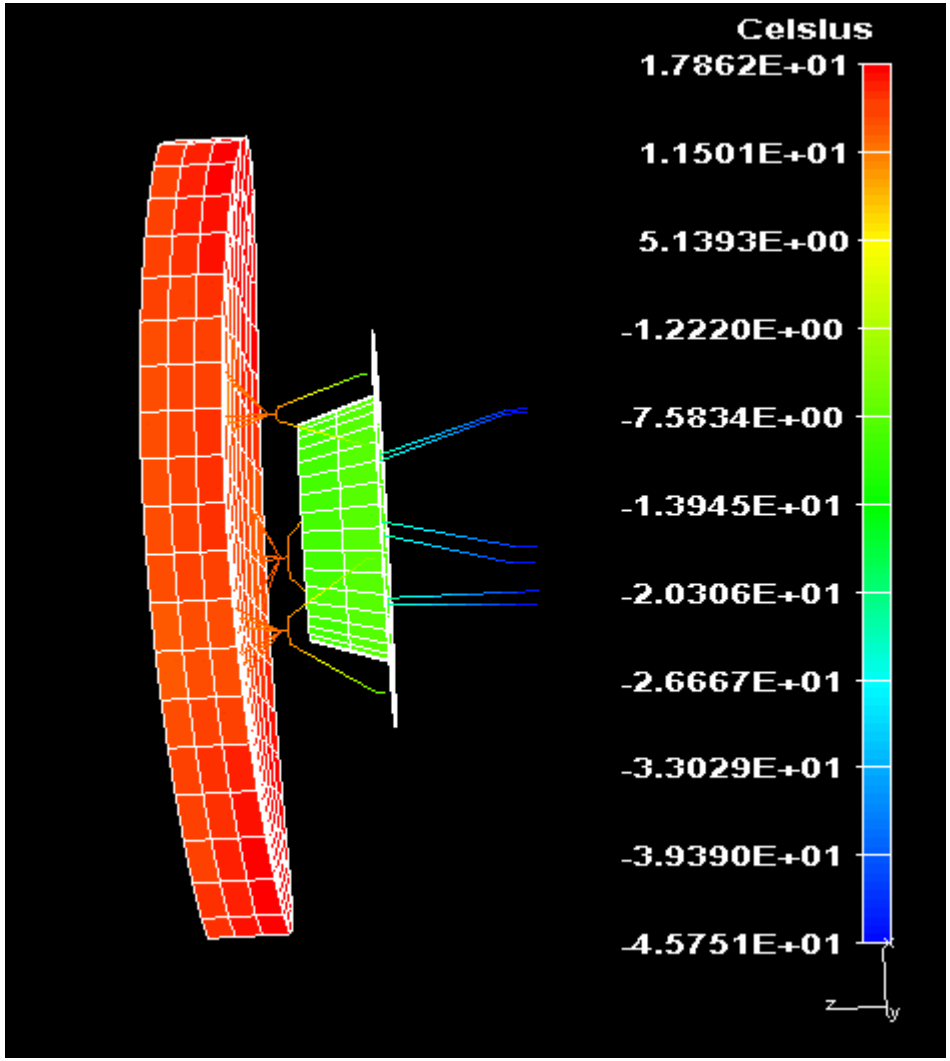
Back-Up

SM Heaters and SM Support Ring Temperatures: 255 deg Roll



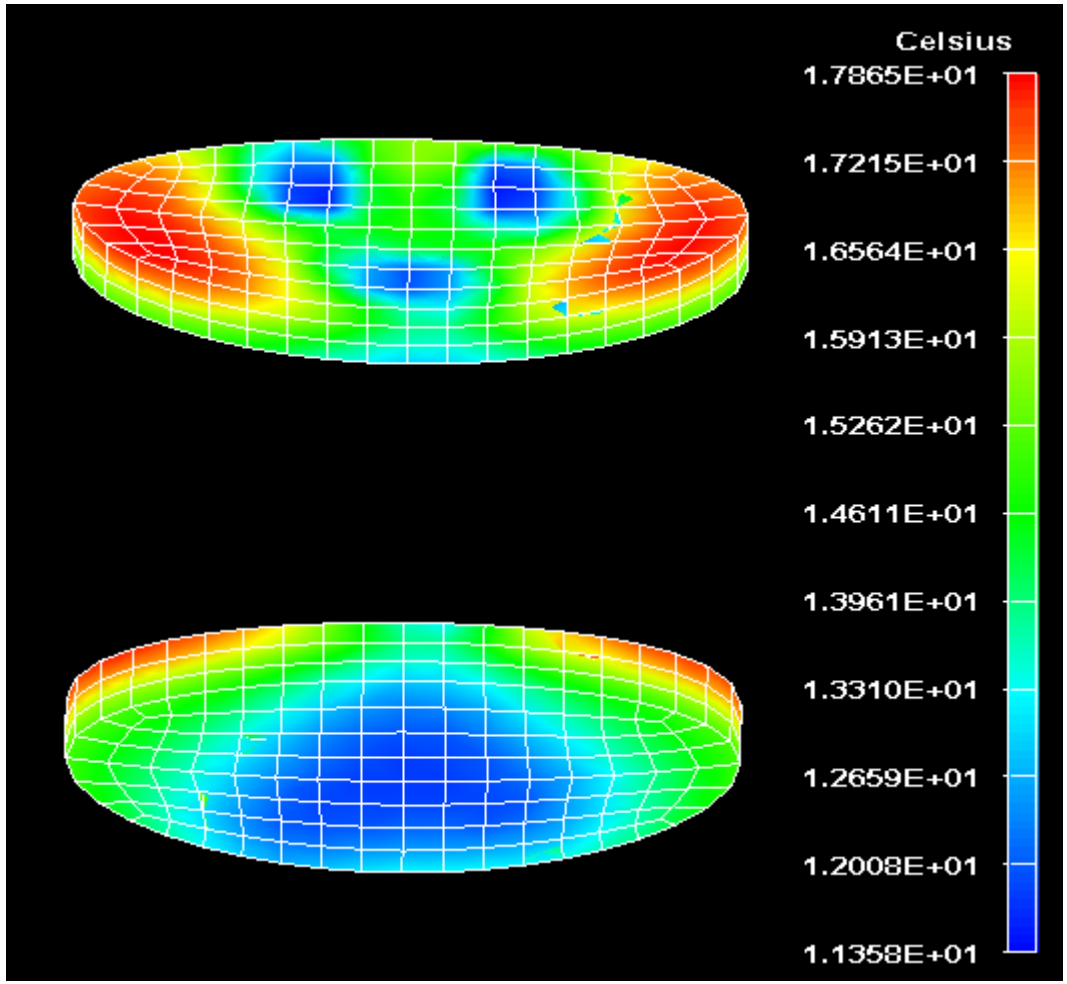
Back-Up

SM, SM Support Ring and Hexapod Temperatures: 255 deg Roll



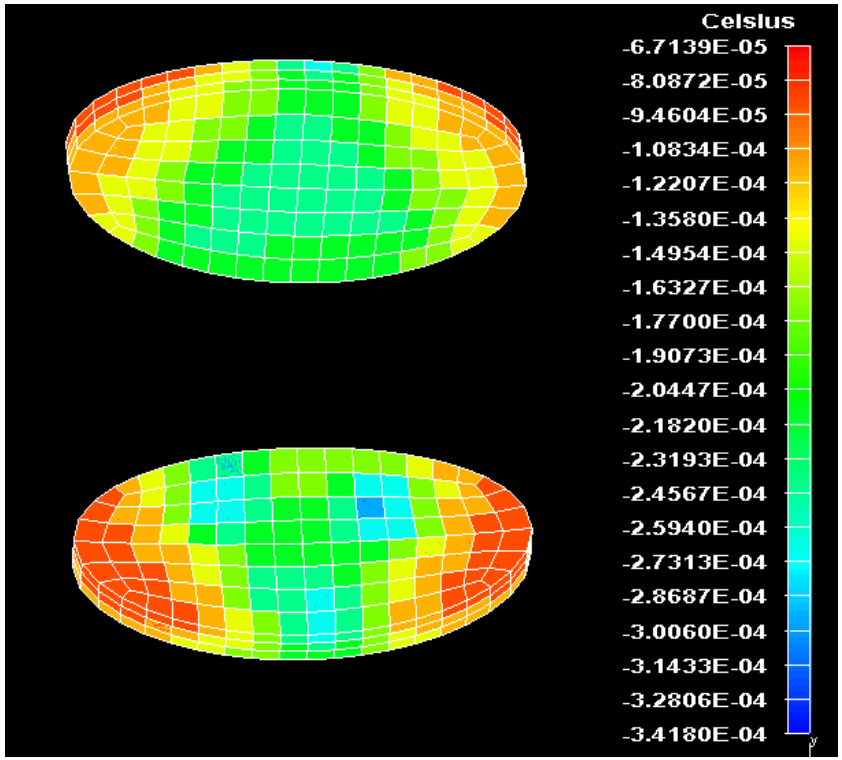
Back-Up

SM Temperatures: 255 deg Roll

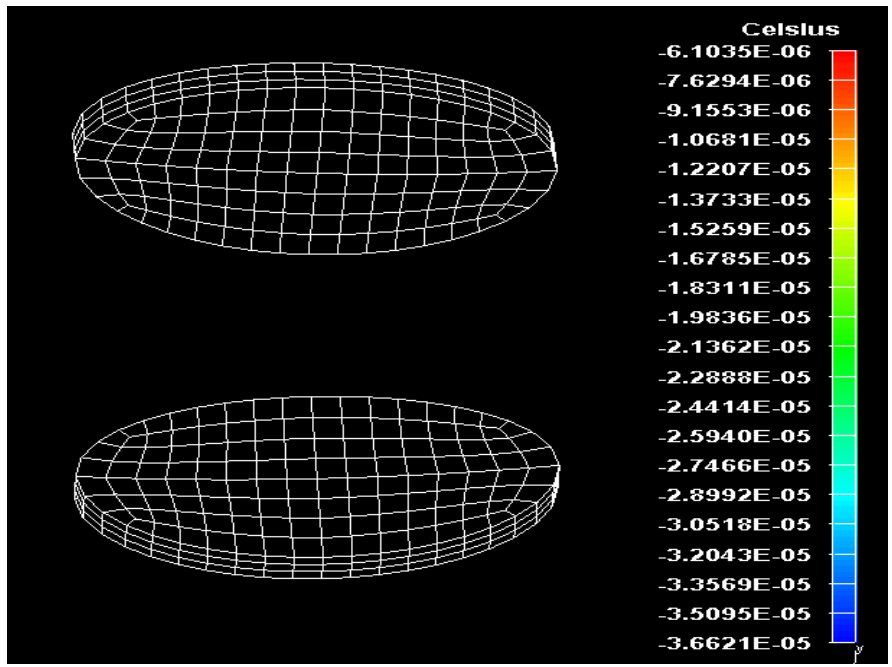


Back-Up

dT of SM during 30 deg. Dither: Hemi-Hemi



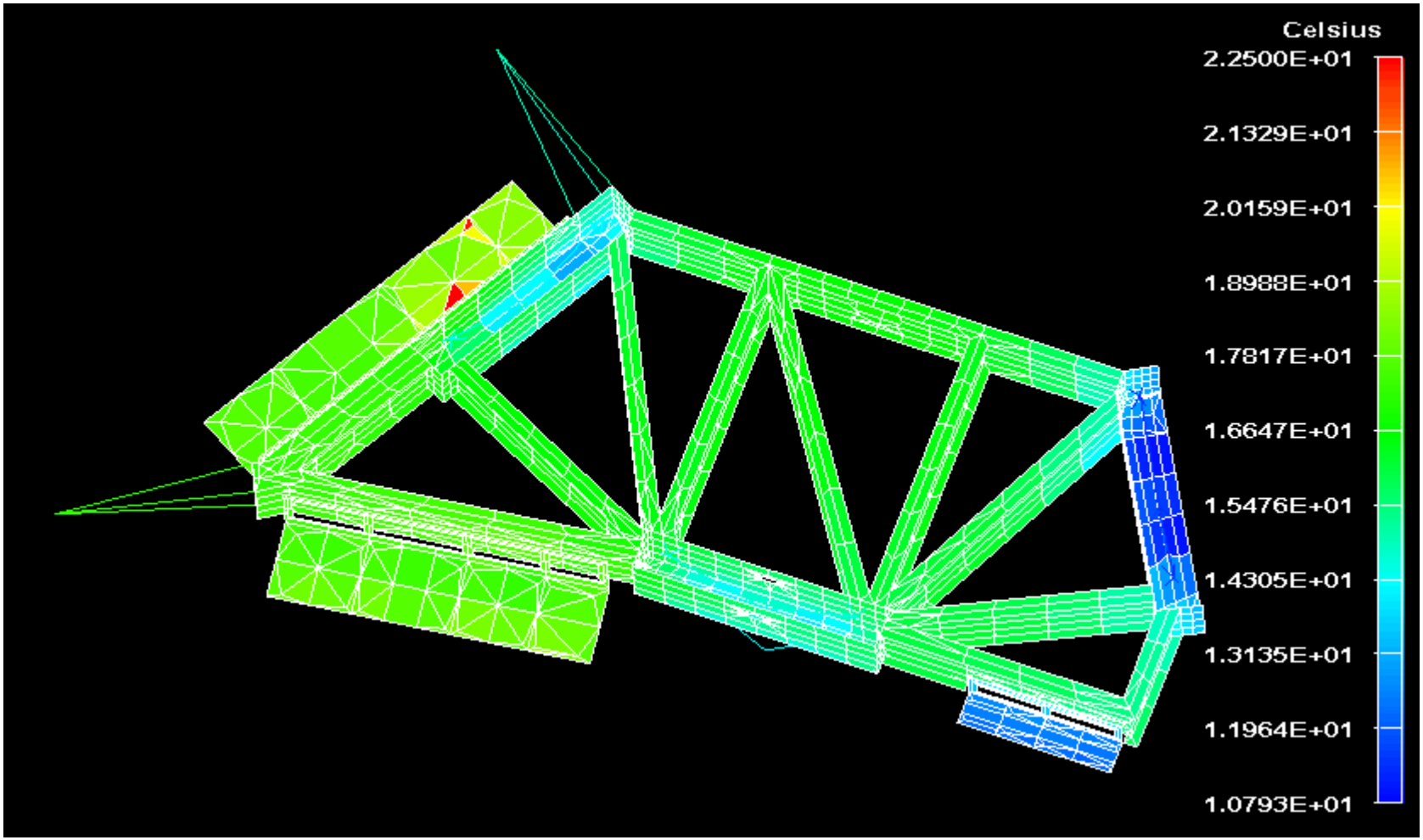
from 195 to 225 deg



from 255 to 285 deg

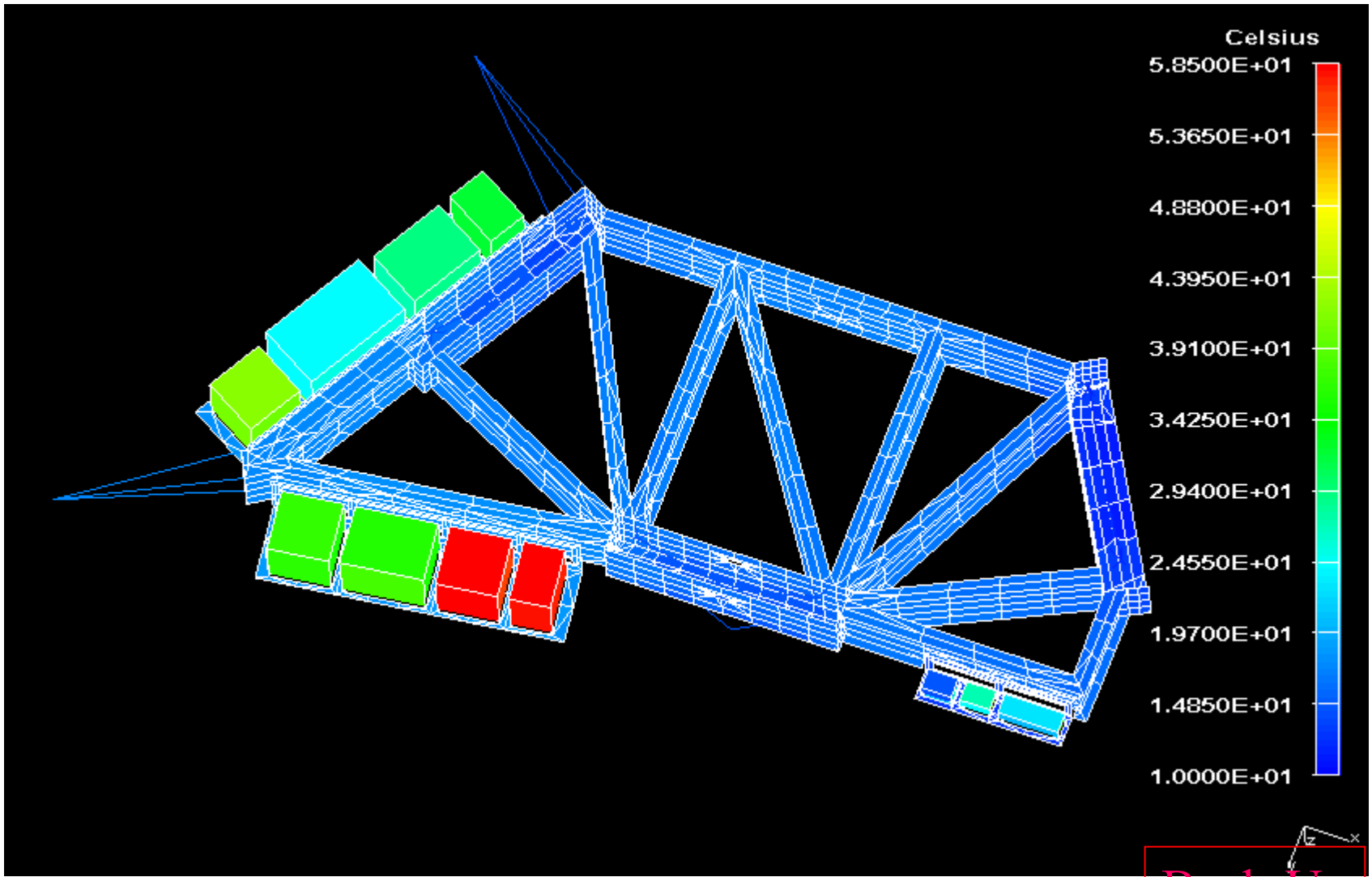
Back-Up

PSS, Electronic Mounting Plate Temperatures: 255 deg Roll

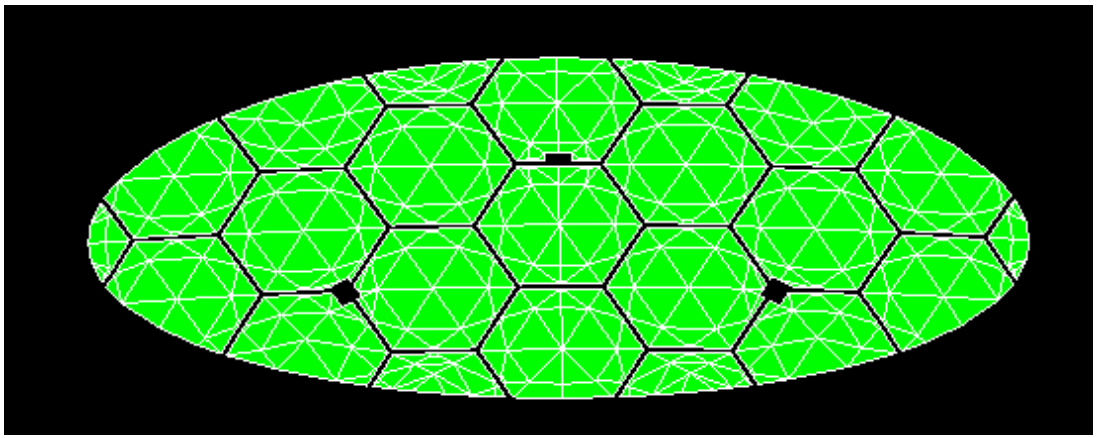


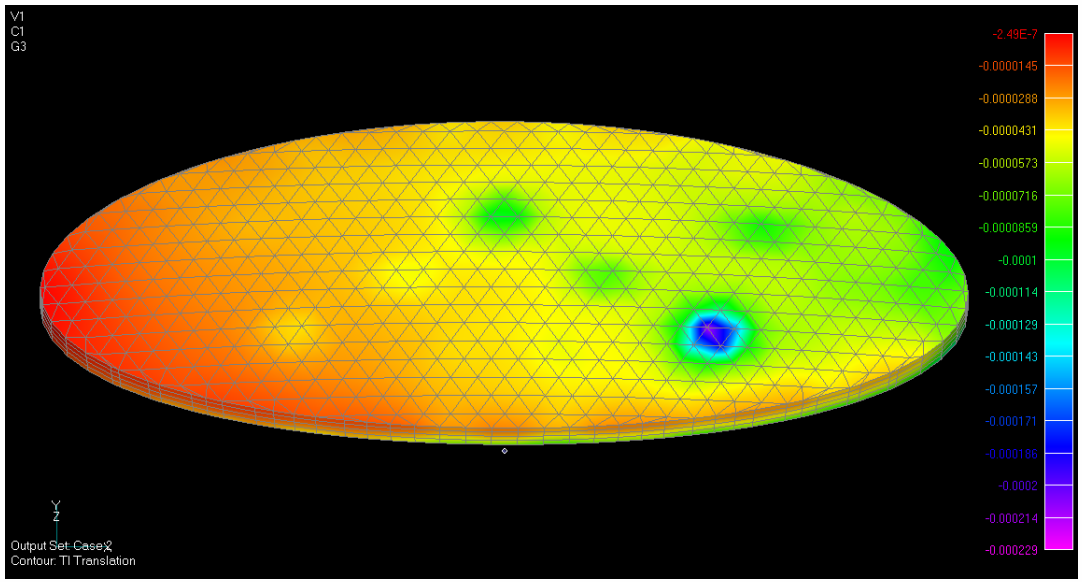
Back-Up

PSS and Electronic Chasses Temperatures: 255 deg Roll



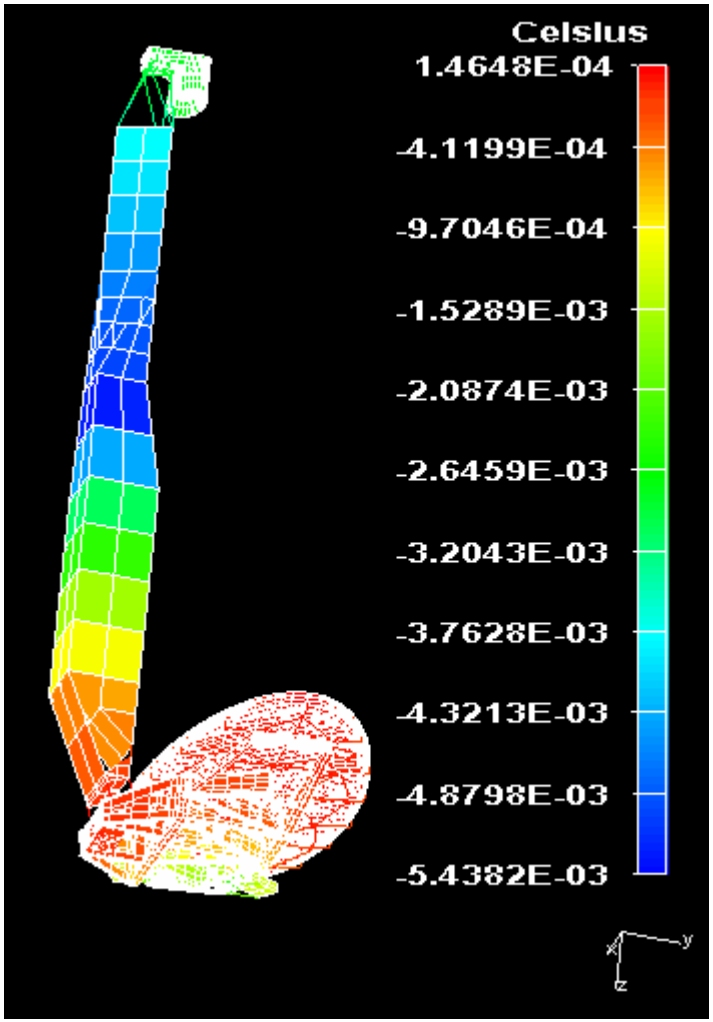
Back-Up



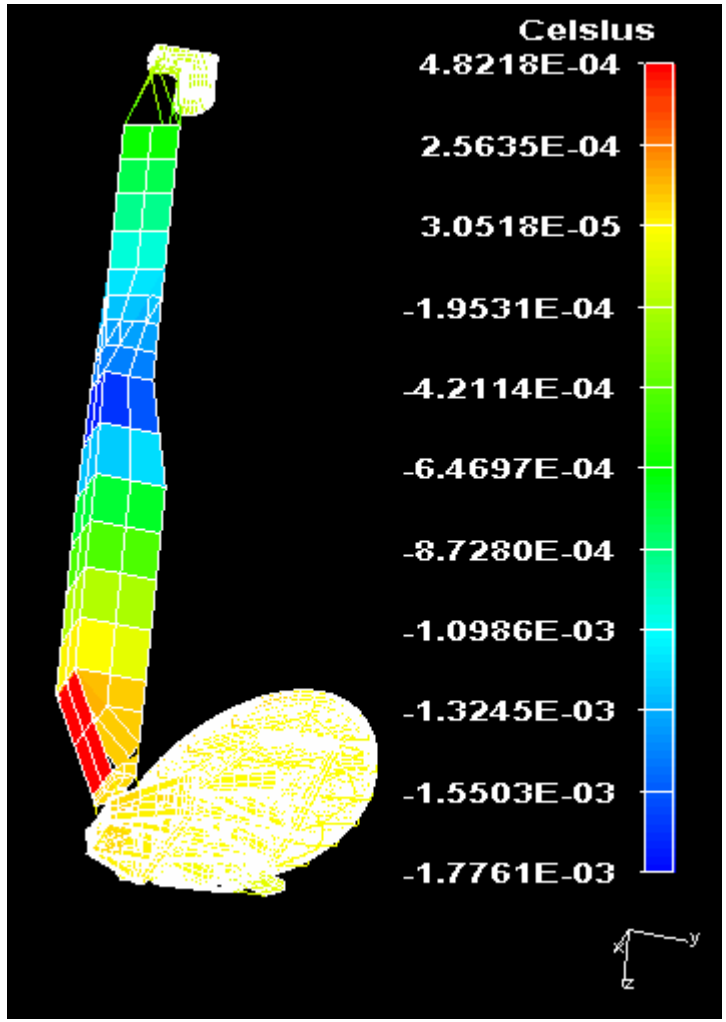

V1
C1
G3
-2.49E-7
-0.0000145
-0.0000288
-0.0000431
-0.0000573
-0.0000716
-0.0000859
-0.0001
-0.000114
-0.000129
-0.000143
-0.000157
-0.000171
-0.000186
-0.0002
-0.000214
-0.000229
Output Set: Case X
Contour: T1 Translation

dT* of Optical Telescope Assembly (OTA) during 30 deg. Dither: Hemi-Hemi

Lockheed Martin
Ball Aerospace & Technologies Corp.
Northrop Grumman Space Technology
TC Technology
nightsky systems



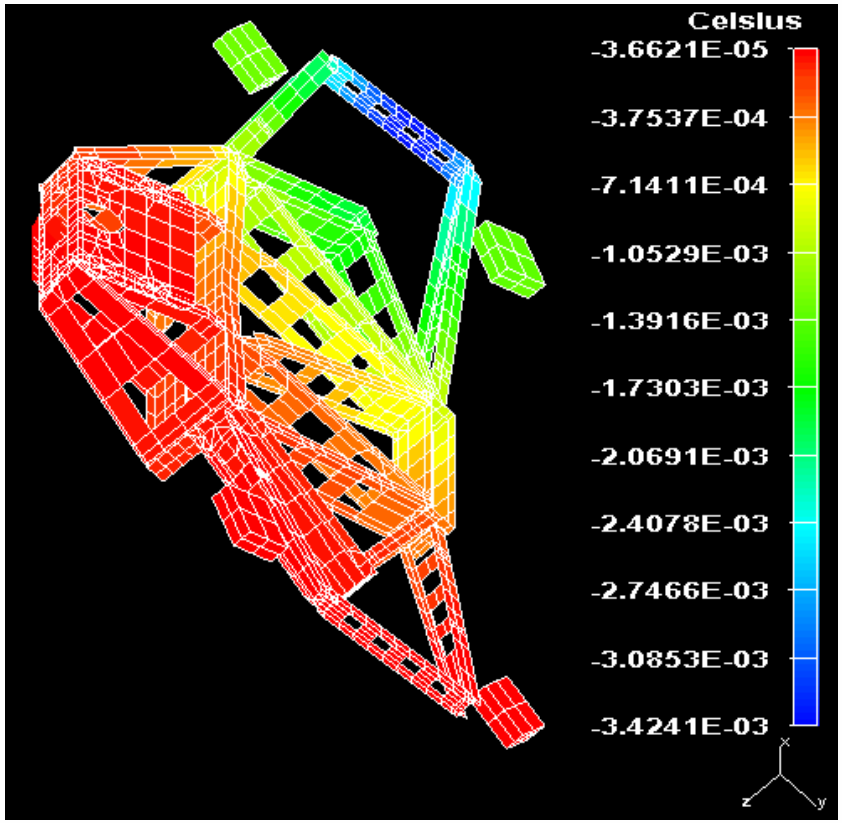
from 195 to 225 deg



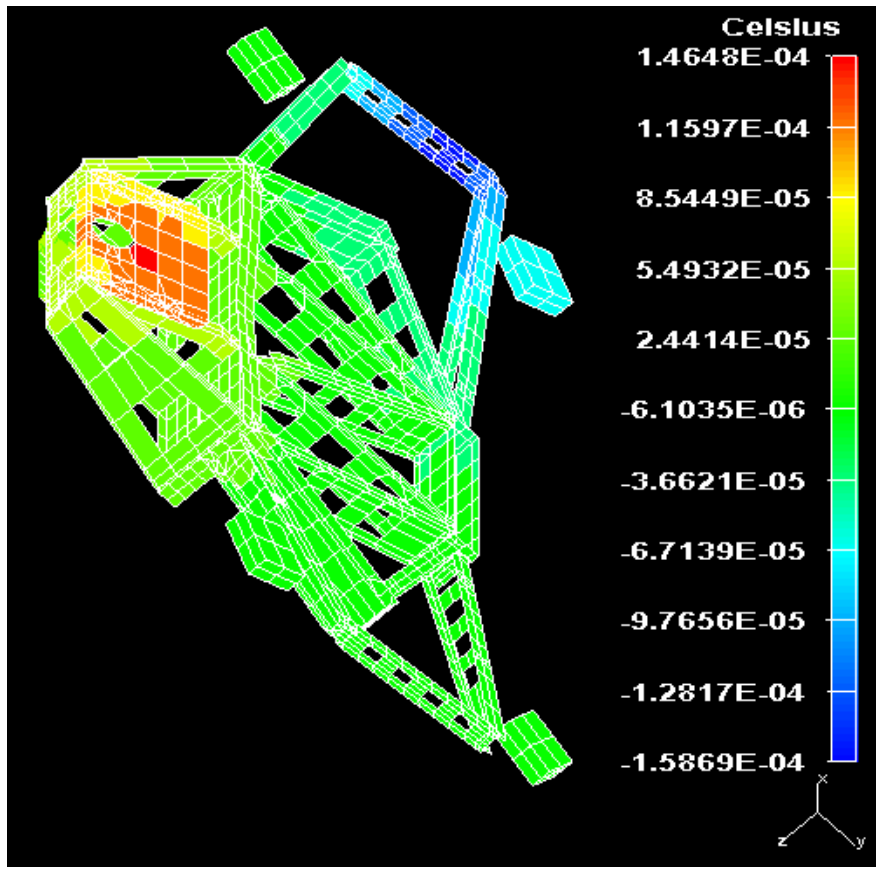
* dT is the temp difference between two steady states

from 255 to 285 deg

dT* of Aft Metering Structure (AMS)and Laser E Boxes during 30 deg. Dither: Hemi-Hemi



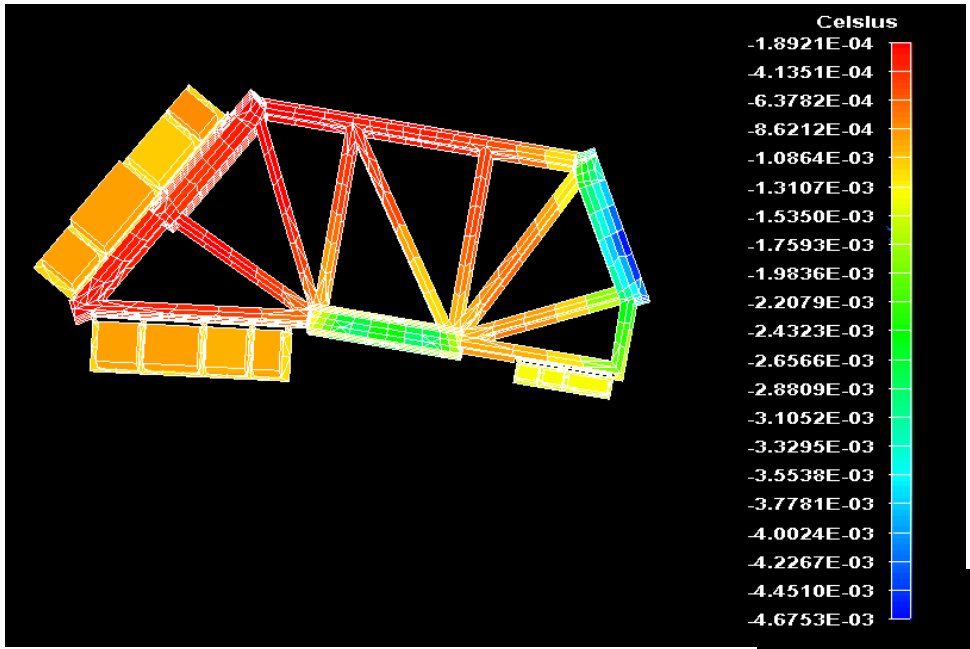
from 195 to 225 deg roll



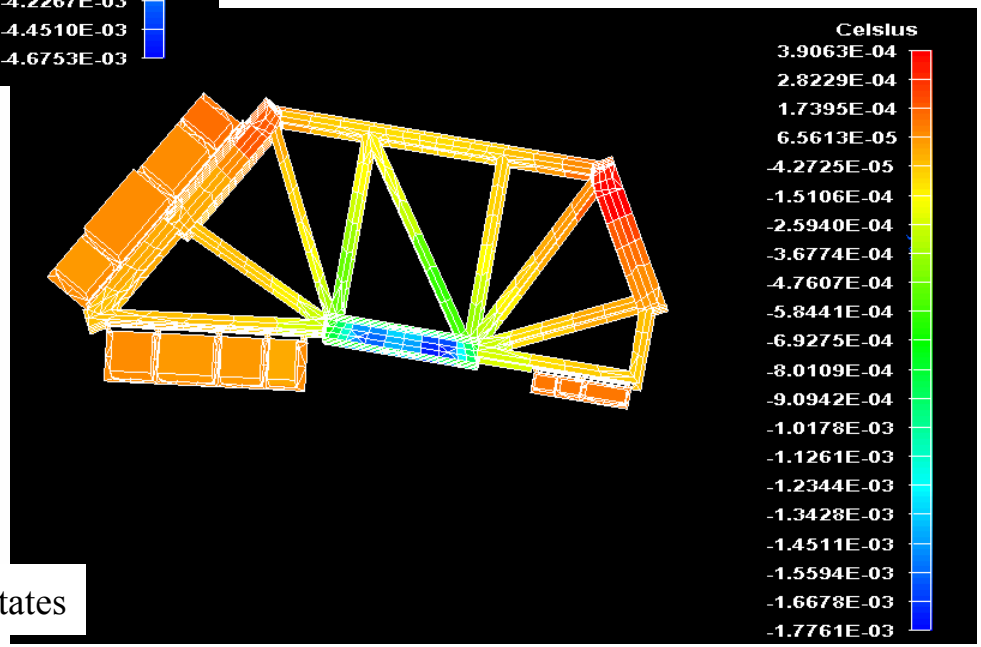
from 255 to 285 deg roll

* dT is the temp difference between two steady states

dT* of Electronics and Payload Support Structure (PSS) during 30 deg. Dither: Hemi-Hemi



from 195 to 225 deg

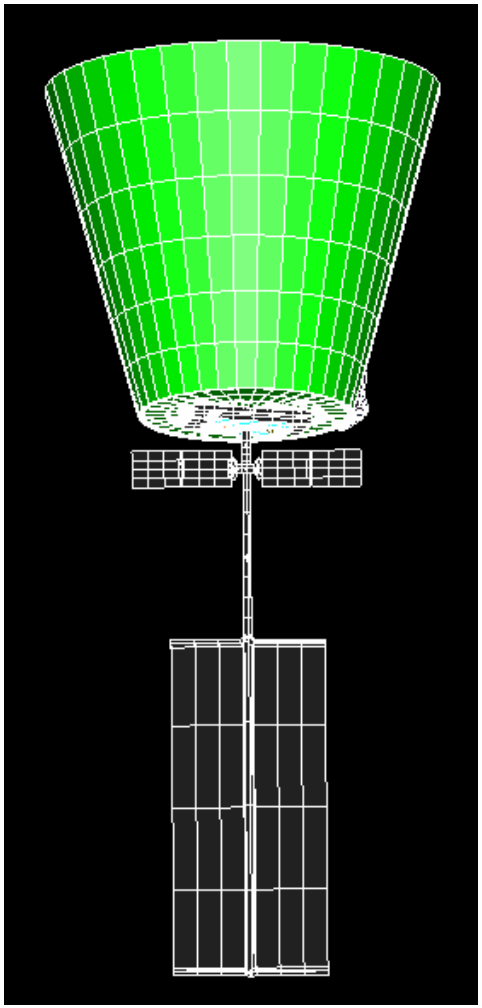


from 255 to 285 deg

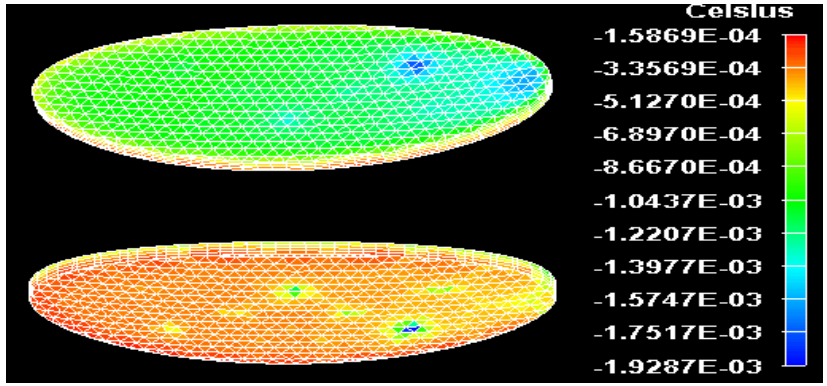
Back-Up

* dT is the temp difference between two steady states

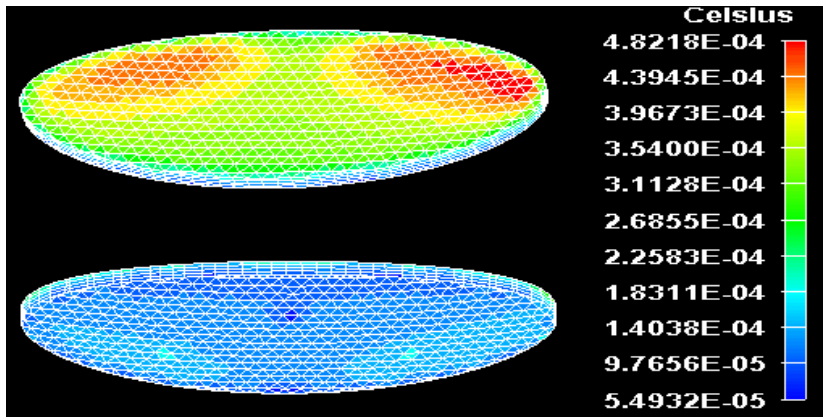
Sun at 75 deg to the optic(telescope) axis



195 deg roll



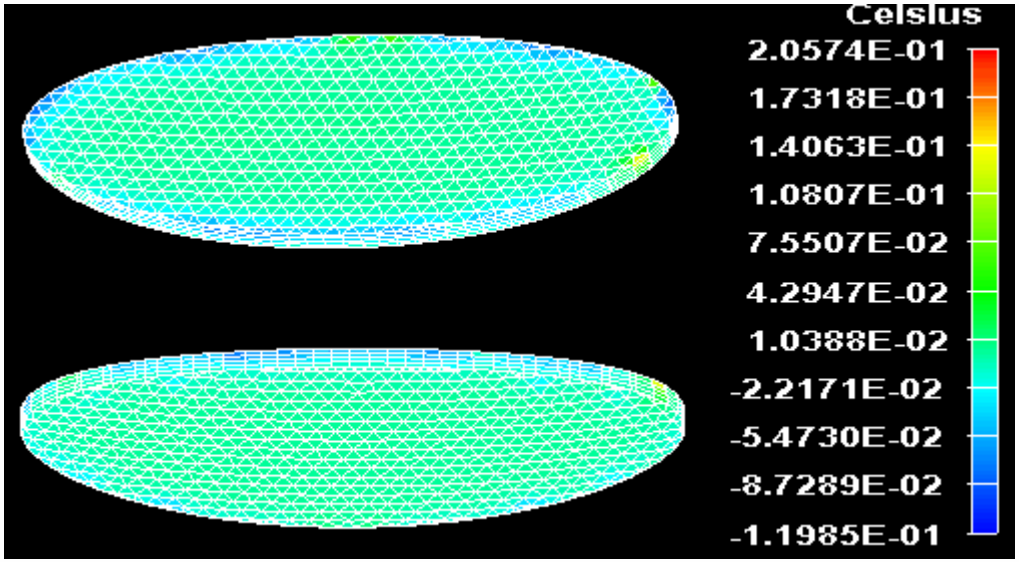
dT during 30 deg Dither from 195 to 225 deg: Hemi-Hemi

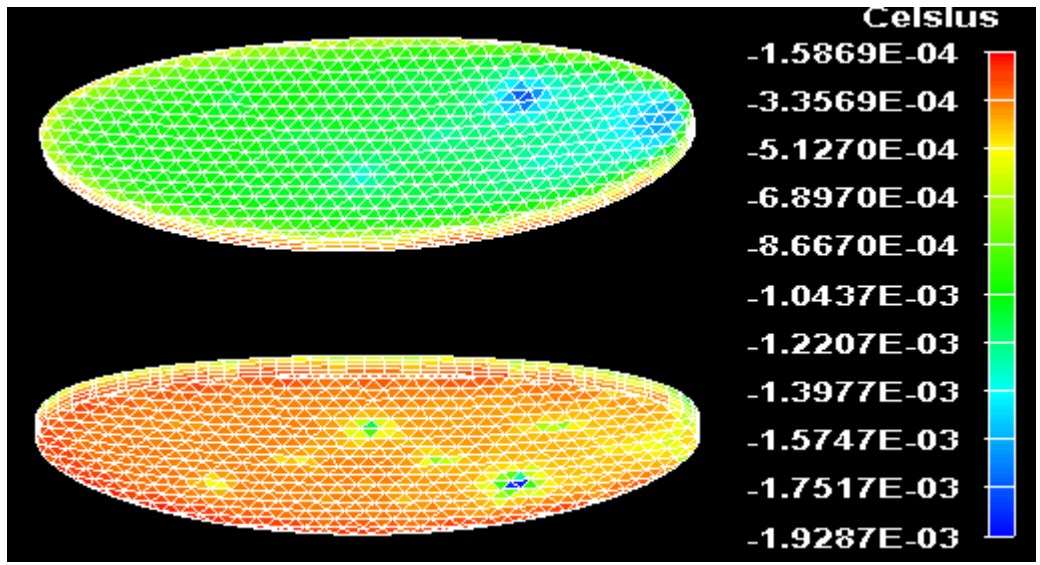


dT during 30 deg Dither from 255 to 285 deg: Hemi-Hemi

Back-Up

Sun at 75 deg to the optic(telescope) axis





Back-Up

LOCKHEED MARTIN
Ball Aerospace & Technologies Corp.
NORTHROP GRUMMAN Space Technology
TC Technology
nightsky systems

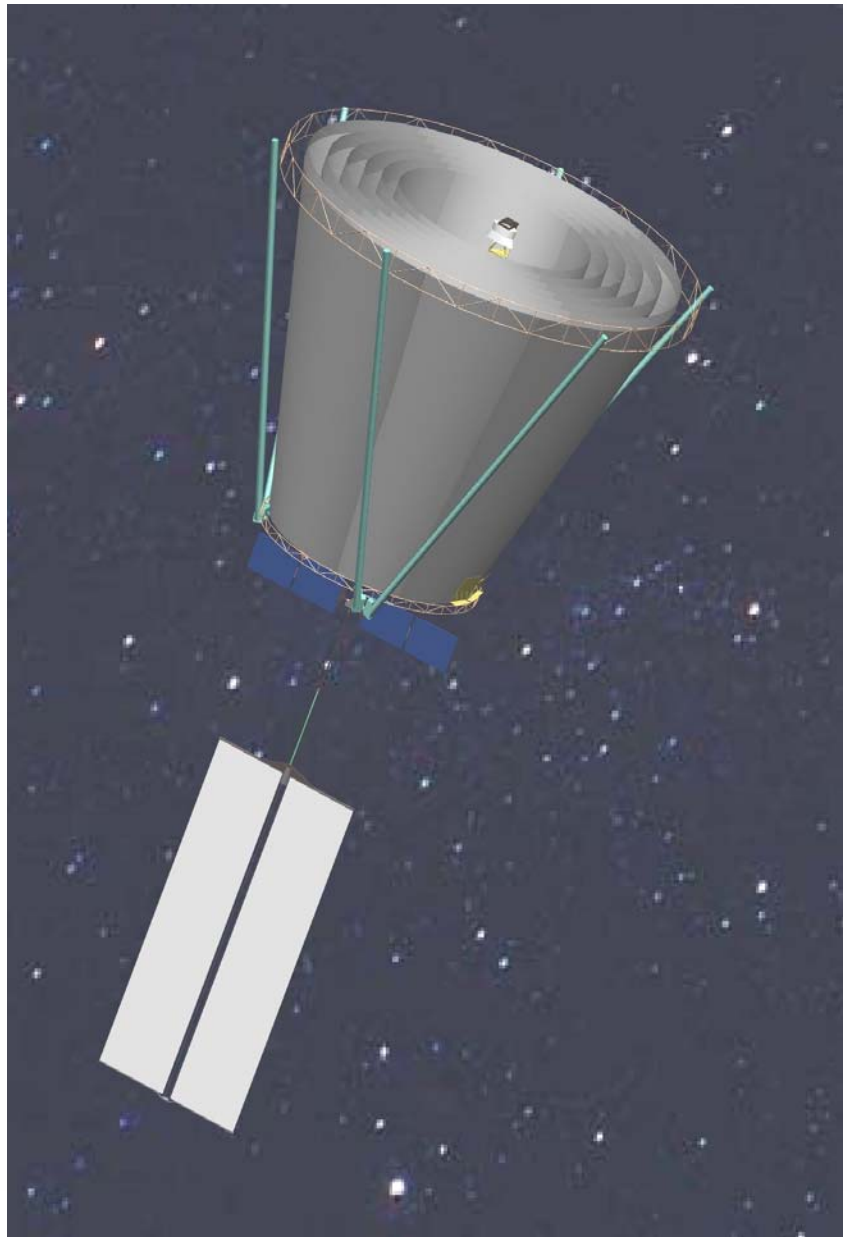
TPF Terrestrial Planet Finder

System Structural Modeling & Performance

Andy Kissil

Contributors:
Eug Kwack, Tim Ho,
Sandra Irish, Ichung Weng

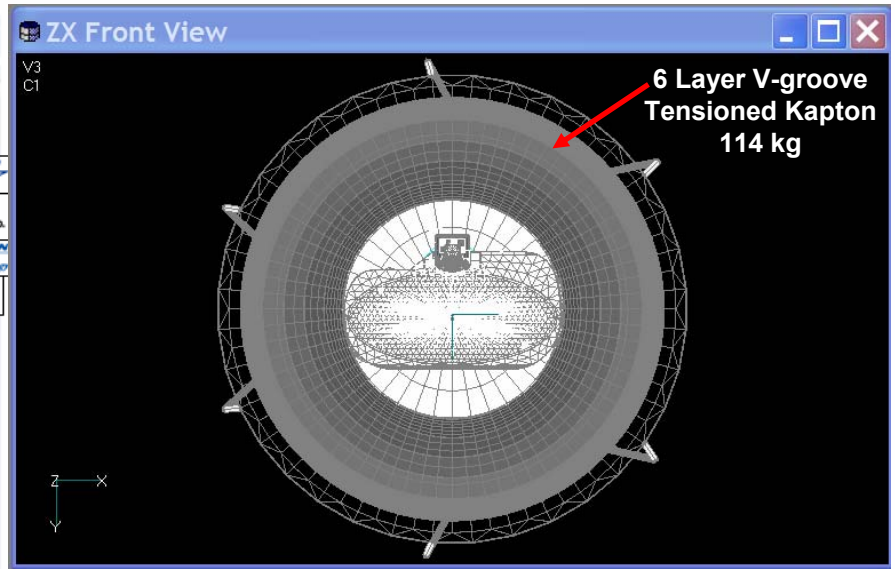
11-12 July 2005

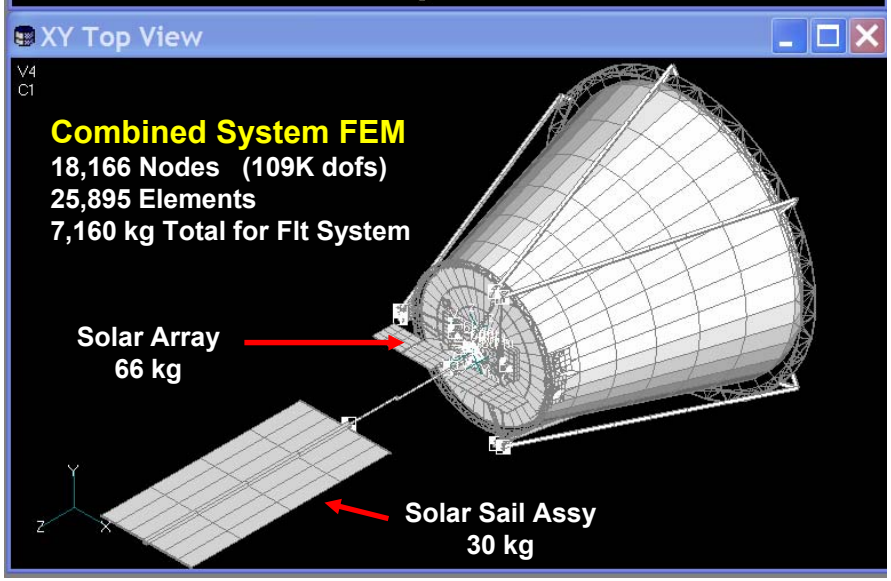


Summary

- **Snap-shot of work to date & current status**
  - **A lot Accomplished, but work is still in-progress**
- **FEM overview**
  - **Model fidelity: size/complexity, mass, idealizations**
  - **Materials**
- **System performance to-date looks very promising**
  - **Constant CTE (Coefficient of thermal expansion)**
    - **WFE due to Primary Mirror Distortion**
    - **Relative Motion of Rigid Optics**
  - **Variable CTE**
    - **WFE due to Primary Mirror Distortion**
- **System Launch Analysis**
- **Conclusions & Future Work**
  - **Computed WFE's & RB motions for thermal disturbance are within error budget**

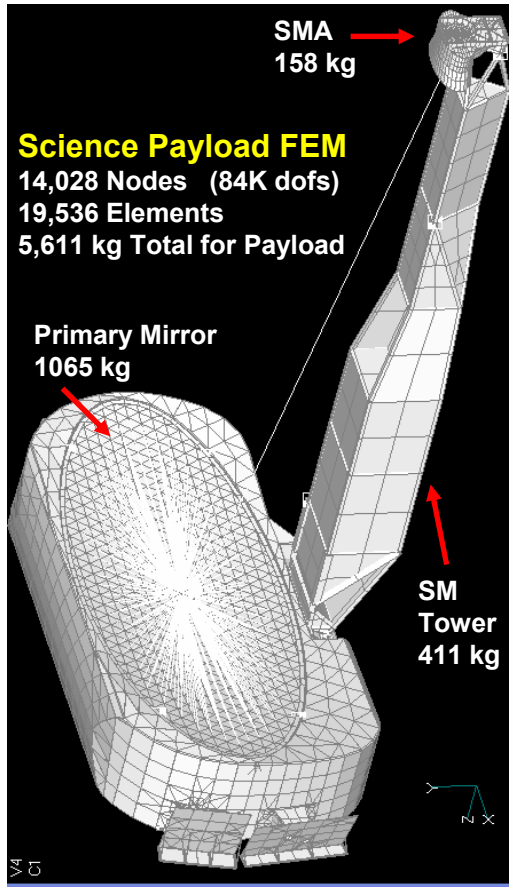
Combined System & Science Payload Finite Element Models Overview

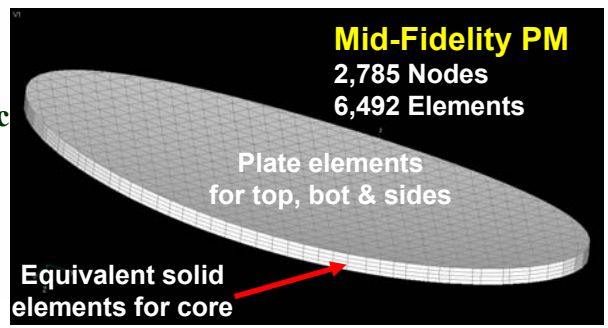




IDEALIZATIONS

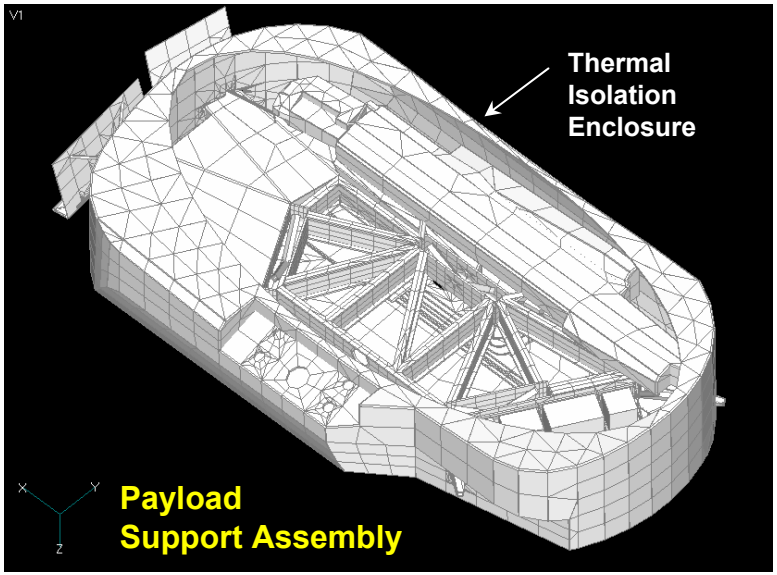
- No hinges, latches or fittings modeled
- No temperature dependent properties
- Uniform properties for like materials
- Lumped & smeared masses for non-struct hardware to match mass-list
- Uniform, linearized model of tensioned membranes to capture geom stiffness
- Mid-Fi PM model captures overall dynamic & thermal distortion, but not local print-thru effects

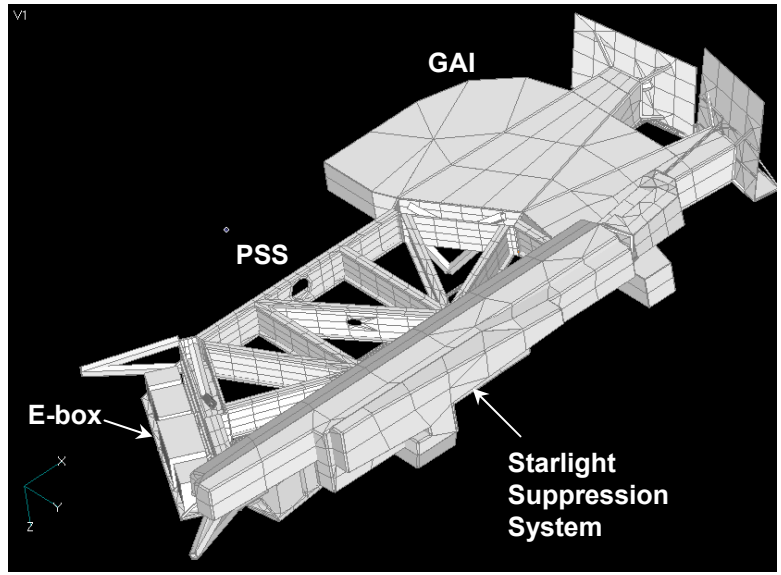


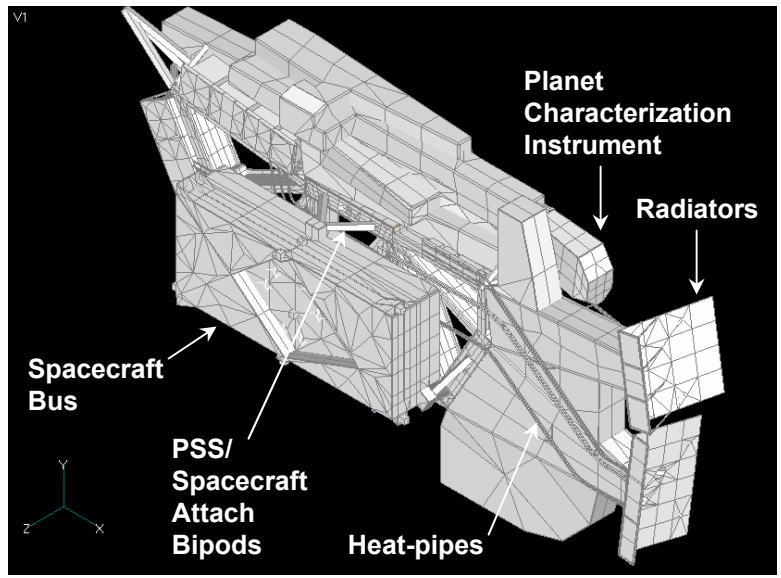


AK1 Andrew Kissil, 7/5/2005

Detailed View of Science Payload & Spacecraft Bus FEM







Typical Materials (no temp dep modeled)

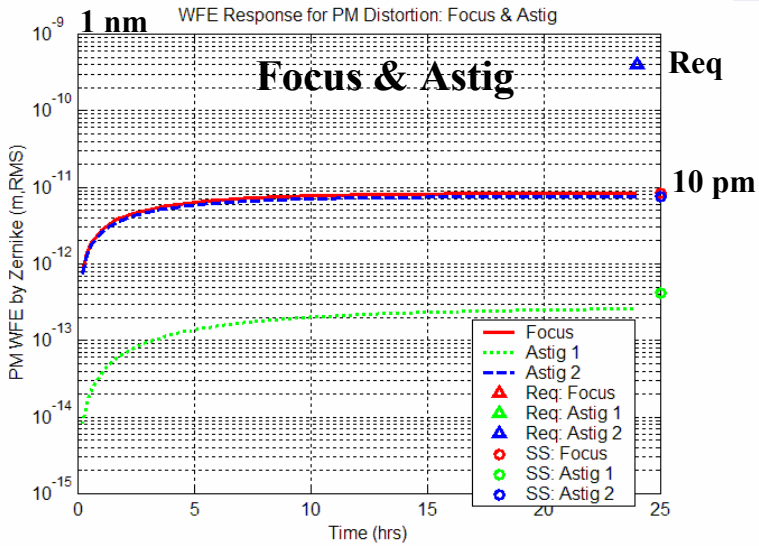
ULE Glass: nom CTE= 10 ppb/C, 2210 kg/m^3
M55J/954 CFRP: nom CTE= -250 ppb/C, 1633 kg/m^3
K1100/954 CFRP: nom CTE= -300 ppb/C, 1886 kg/m^3

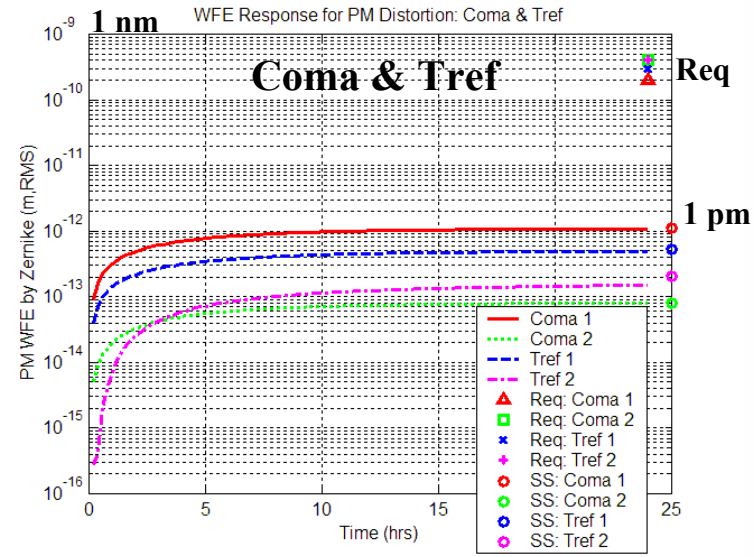
Mass Summary for Items Shown

Thermal Enclosure = 479 kg
PSS = 368 kg
Starlight Suppression Sys = 422 kg
General Astrophysics Instr = 150 kg
Planet Characterization Instr = 20 kg
Spacecraft Bus = 833 kg

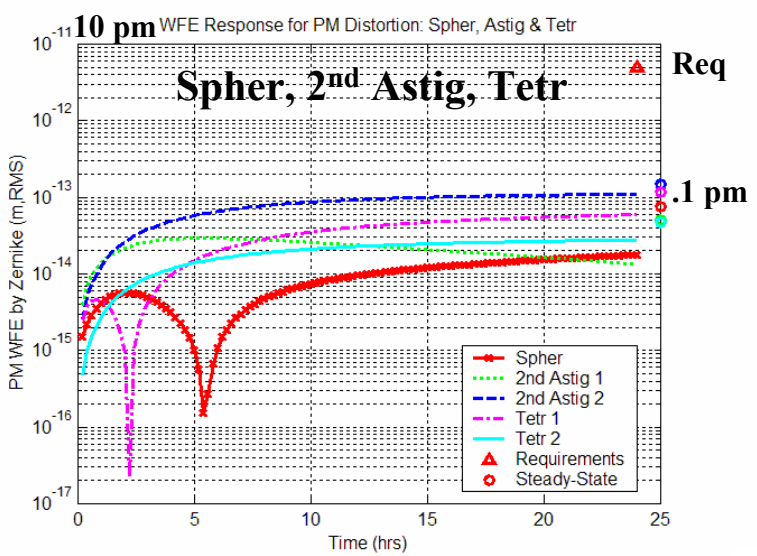
WFE Responses for PM distortion Transient & Steady-State

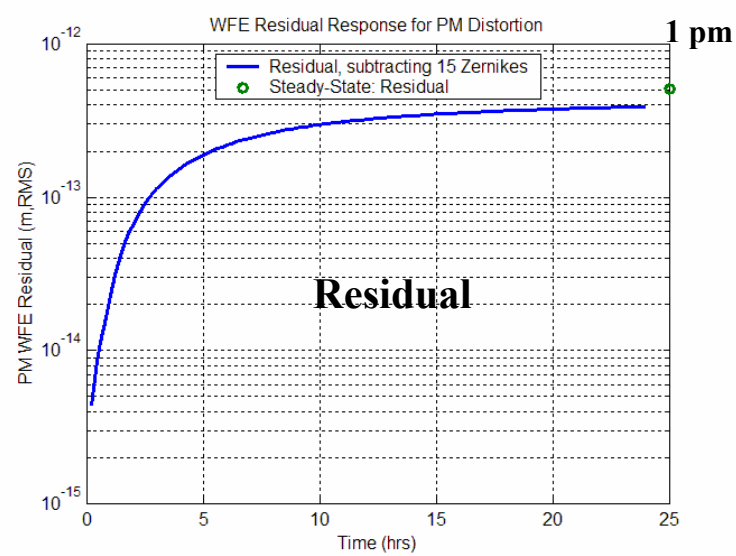
30 deg Dither (195-225)





Uniform PM CTE (10 ppb/C) Assumed

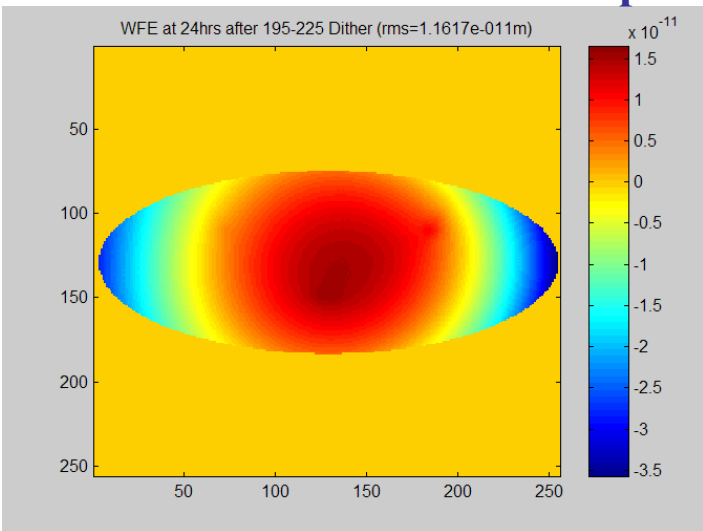




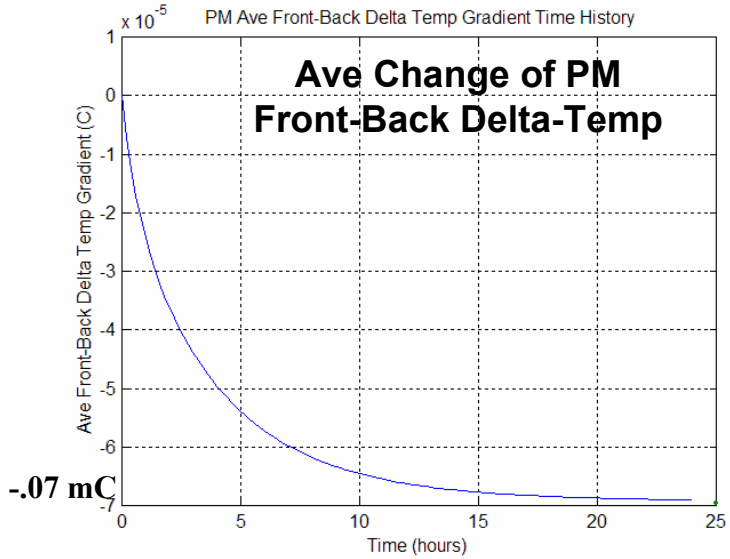
Focus & Astig Vary with Changes in PM Front-Back Delta-Temp

30 deg Dither (195-225)

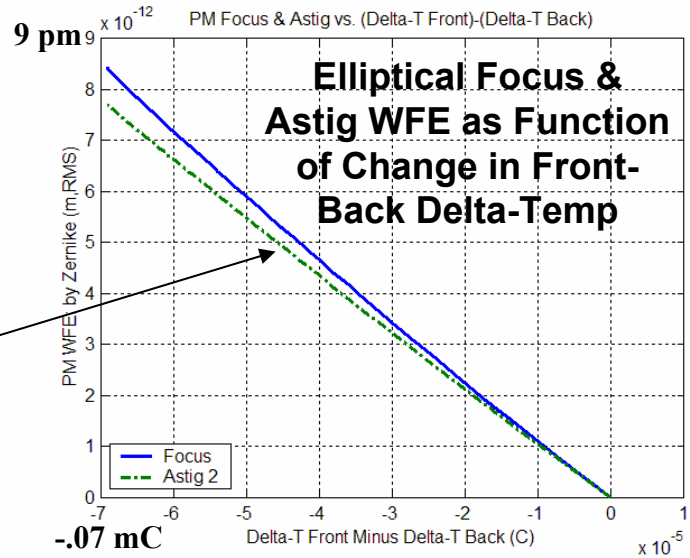
WFE Response is Dominated by Circular Focus: Bending of PM Induced by Changes in Front-to-Back Delta-Temp



WFE= 11.6 pm rms @ 24 hrs after Dither



Uniform PM CTE (10 ppb/C) Assumed



~100nm rms / deg C

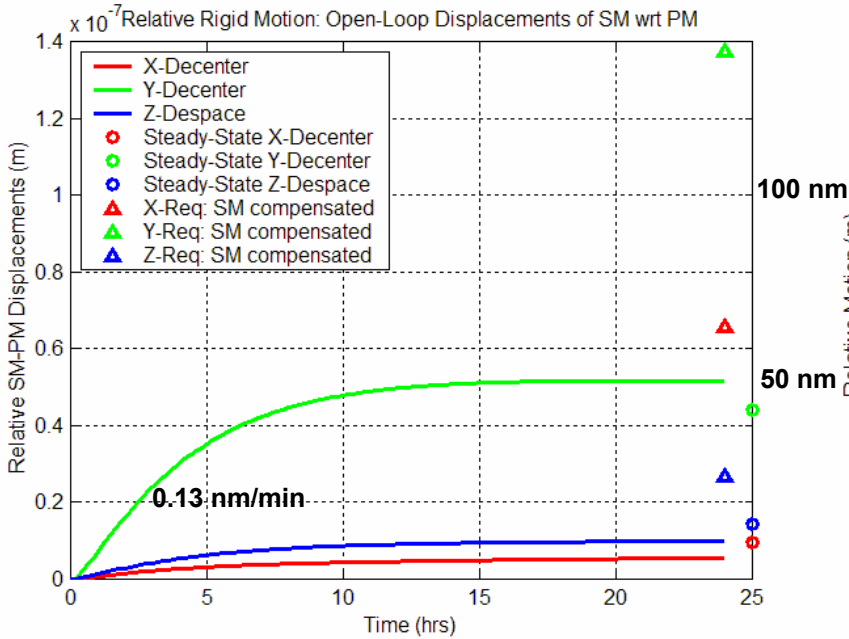
Slope Verified by Independent Front-Back Delta-Temp Only Run

Relative Motion of Rigid Optics

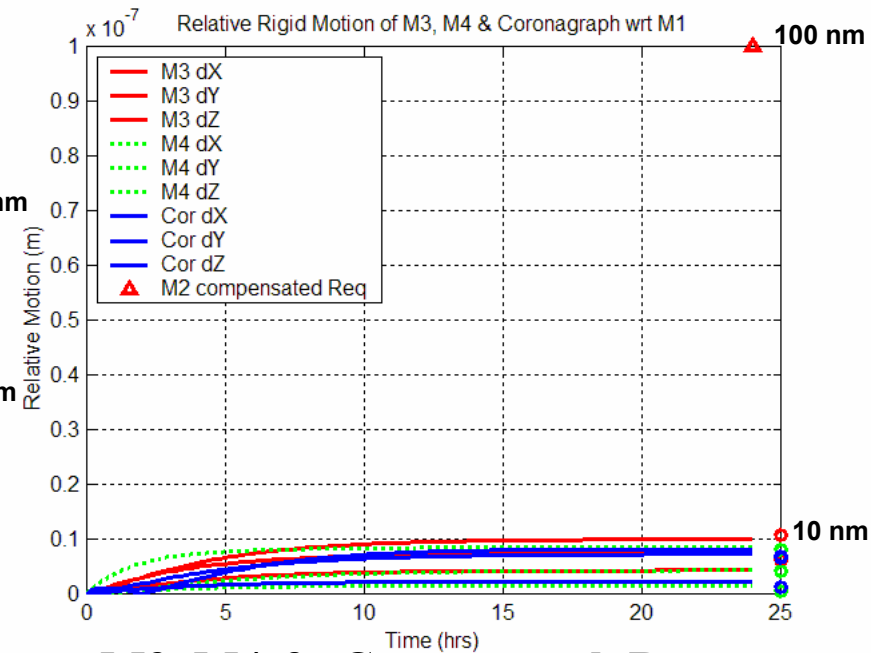
Open-Loop Response
30 deg Dither (195-225)

All Optics Motions are Relative to Primary Mirror

Motion Budget Values Derived from Beam-Walk Effects



Secondary Mirror



M3, M4 & Coronagraph Box

- All rigid optics motions are within error budget
- M3 & M4 are the first two fold mirrors in train
- Assumed constant CTEs (will look at effects of CTE variability)
- No hinges, latches or fittings modeled yet

Monte-Carlo Study of Primary Mirror CTE Variation

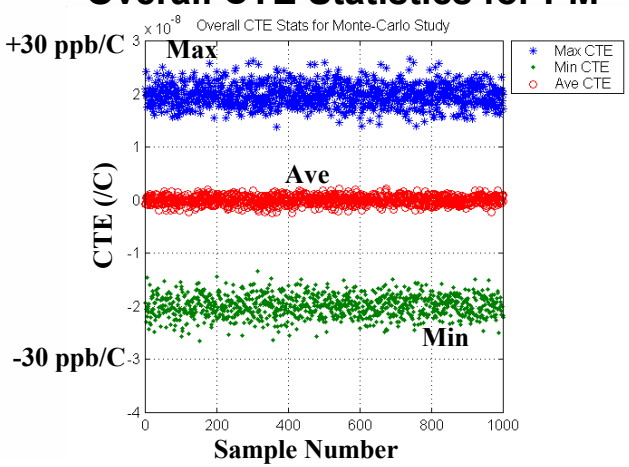
- **Modeling & Analysis done using IMOS: generated 1000 Random (with structure) element CTE distributions**
- **Each of the 92 regions (23 segs x 4 layers) of the mirror were given CTE variations four functions: bias, side to side, radial & axial**
- **Function parameter values randomly set consistent with TDM CTE Specifications**

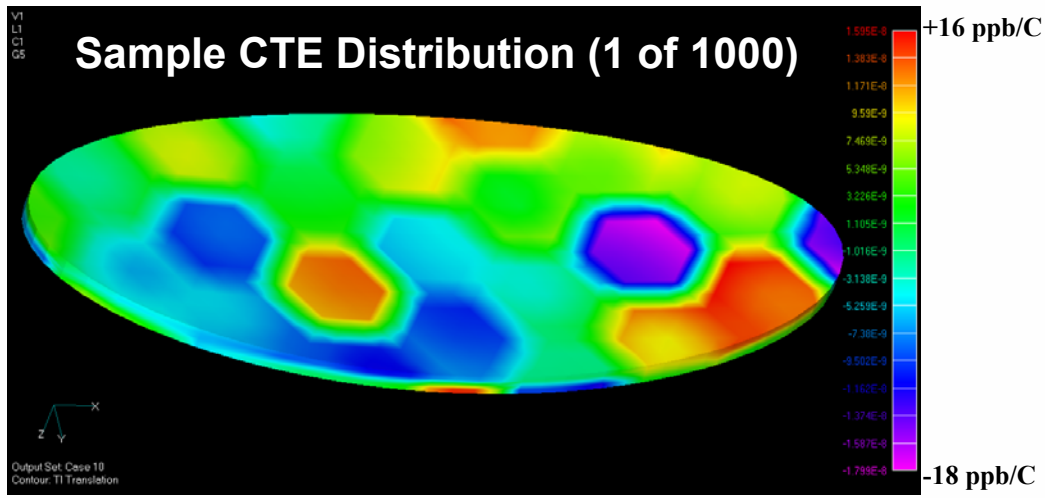
TDM PDR CTE Specs

(used by Kodak)

INITIAL MIRROR CTE TOLERANCES		
No.	**Description**	**Tolerance (ppb/C)**
1	Weighted Blank Average	+/- 10
2	Core Segment Axial Gradient	+/- 10
3	Core Segment Radial Range	< 15
4	Max Core Segment-Segment Average Delta	< 10
5	Face Plate Axial Gradient	+/- 5
6	Face Plates Pt-to-Pt Difference	< 5
7	(Face Plate Average) - (Core Segment Average)	+5 to +15

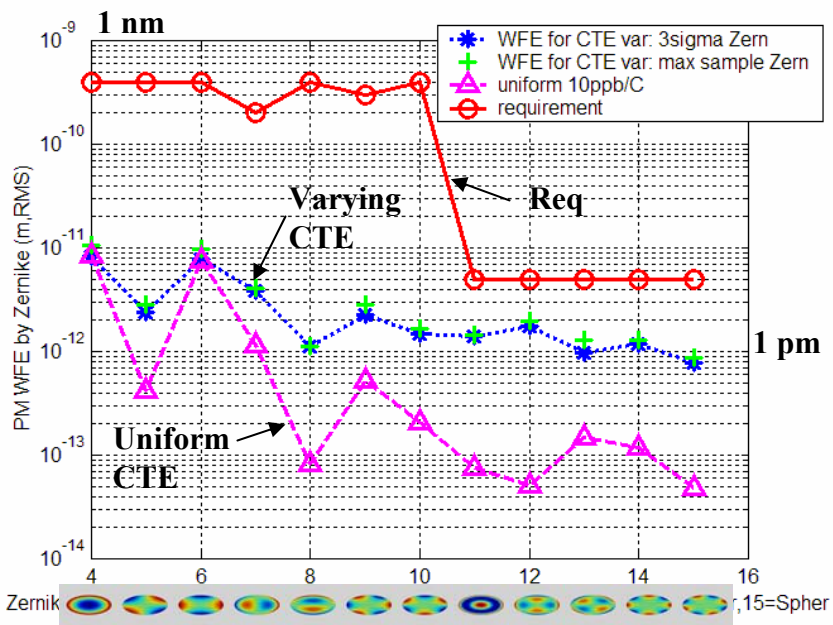
Overall CTE Statistics for PM





Monte-Carlo Study of Primary Mirror CTE Variation

Steady-State Dither Results
30 deg Dither (195-225)



- **Current WFE performance is within error budget** (more conditions consid in future)

  Can be significantly improved with segment positioning based on measured CTEs
- **Need to consider CTE variability**: uniform CTE assumption is not conservative
- Can determine allowable **PM CTE tolerances** with this type of analysis

System Launch Analysis

Normal Mode Frequency

LV Payload Req (Delta IV-H): 8Hz Lat, 30Hz Axial

Computed from FEM: 7.4Hz Lat, ~25Hz Axial
Close to req freq - can be improved

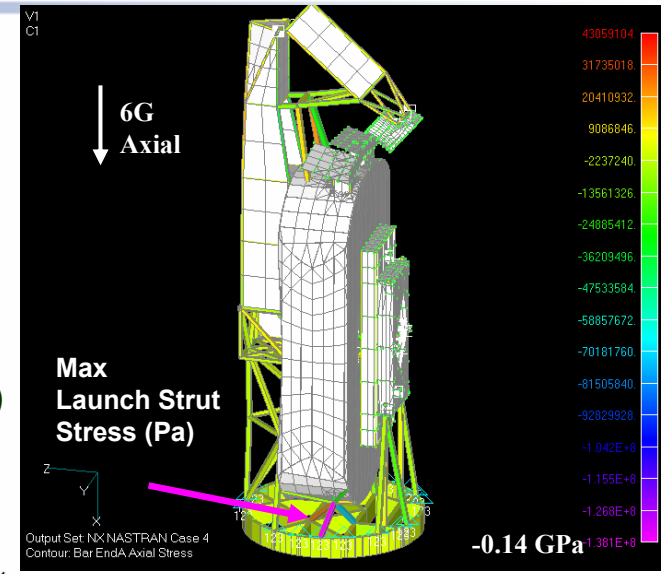
Non-compliance is not a big issue - CLA

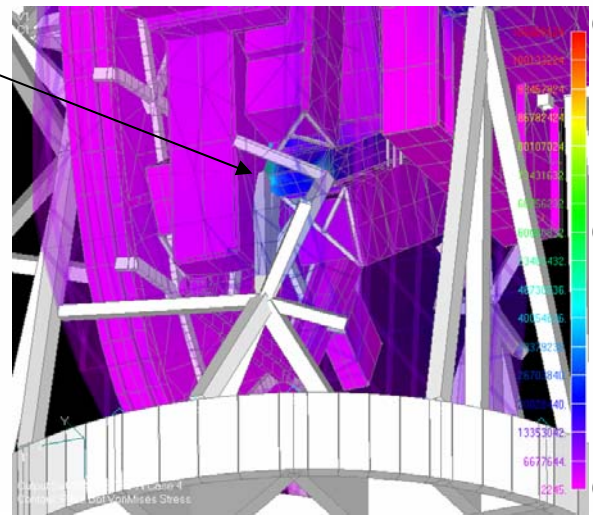
Stress (Combined 6G Axial & 0.5G Lateral, Quasi-static)

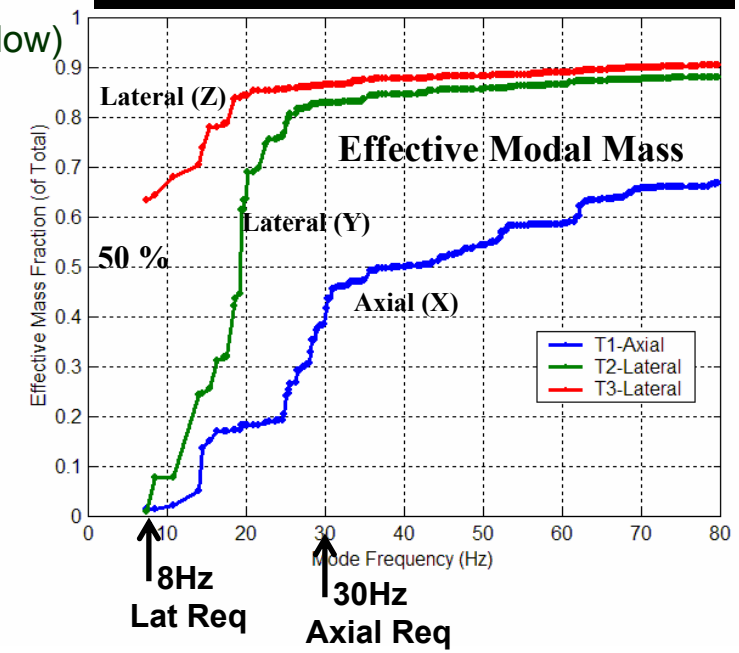
Check that stresses are not excessive

PSS (M55J): **~0.06 GPa (9 ksi)** (~45 ksi Allow)

Strut (K1100): **~0.14 GPa (19 ksi)** (~36 ksi Allow)







Wrap-Up

Conclusions

- **Toolsets work well**, and are getting better (looking forward to significant capability increase shortly)

  Lessons-learned: problems encountered & solved (or temporarily worked-around)
- **Currently, all computed WFE's & RB motions for thermal disturbance are within error budget**
- **We need to account for CTE variation in PM:** Taking CTE variation into account generally results in higher WFEs than assuming uniform CTE of 10 ppb/C
- **Focus & Astigmatism are biggest contributors to WFE**

  Due to changes in PM front-to-back delta-temps
- **Design feasibility looks good: no major road-blocks**

  Keep in mind the many idealizations made so far (snapshot): more detail modeling to follow

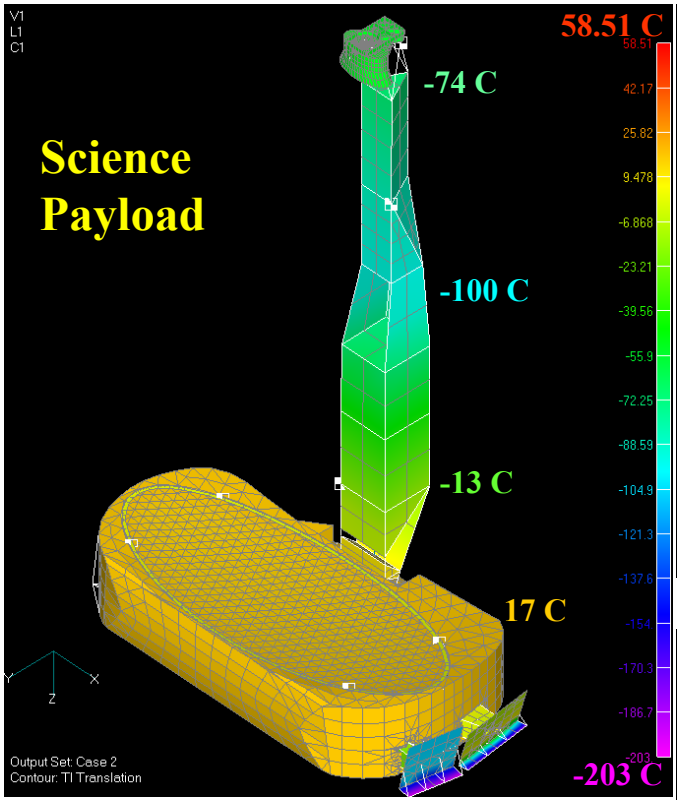
Future Studies

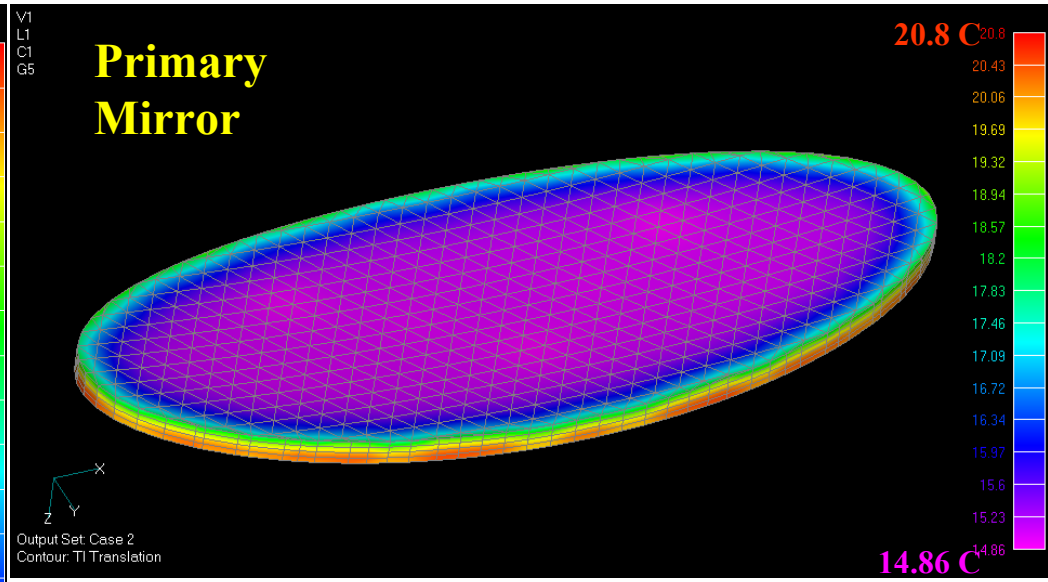
- Look at effects of **Sun locations** behind Telescope (including shadowing), and **heater power control**
- **Optimize launch support structure**: reduce mass & increase stiffness
- **Optimize whole Fight System**: reduce mass & improve performance

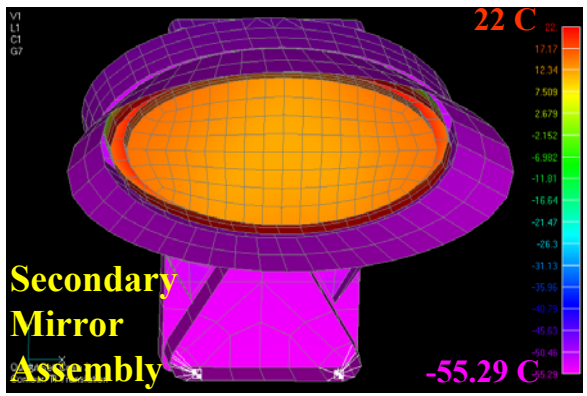
  Look at **material trades, variability & light-weight sections**
- **Quantify analysis tool accuracy & precision** (Testbed correlation will provide ultimate validation)
- Proceed to **FB2 Design & Modeling, and more detail** added

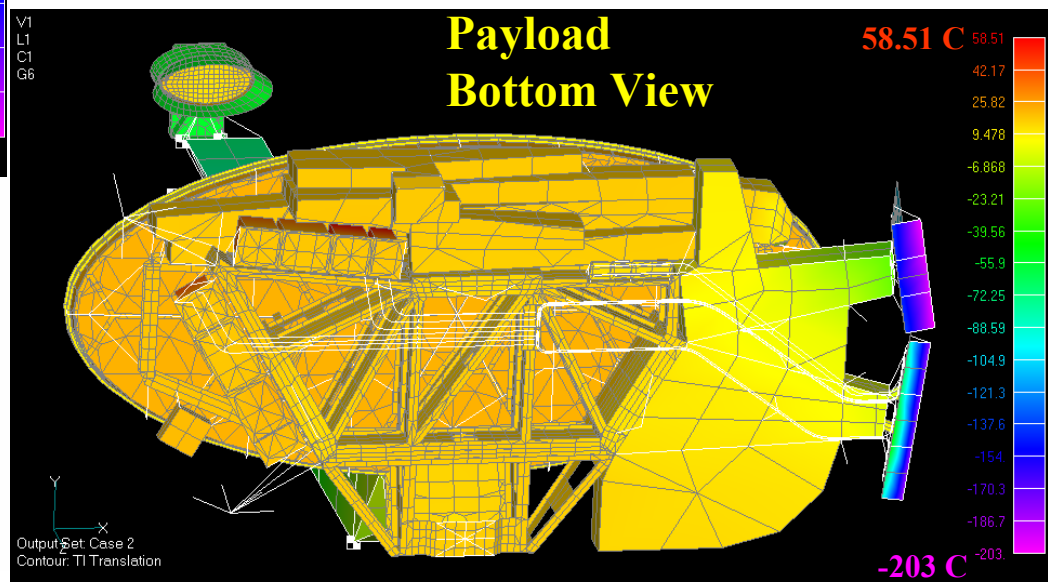
Backup Slides

Temperatures for 195deg Sun Angle (deg C)









TPF Terrestrial Planet Finder

Delta-Temps for 30 deg Dither (Steady-State, 195-225, deg C)

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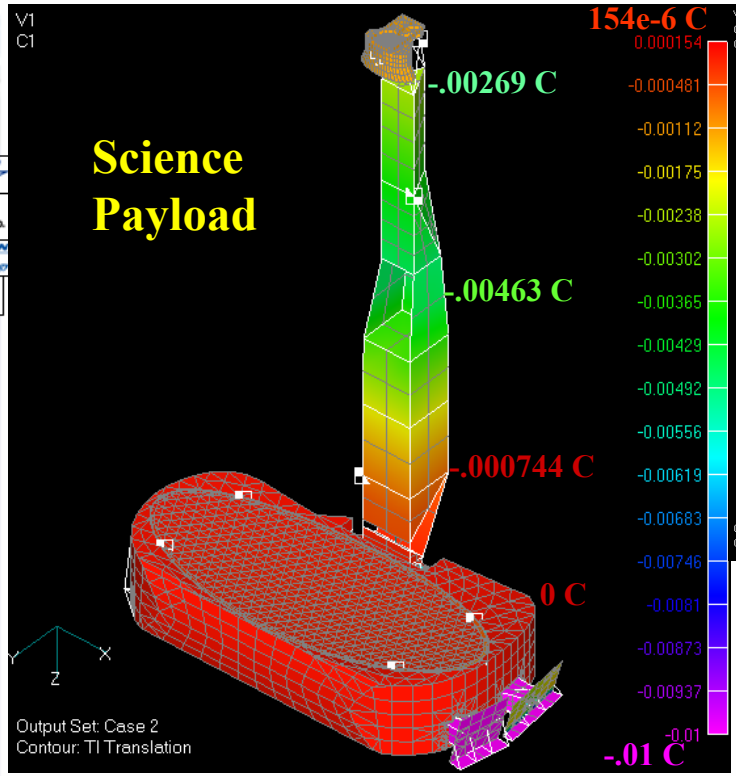
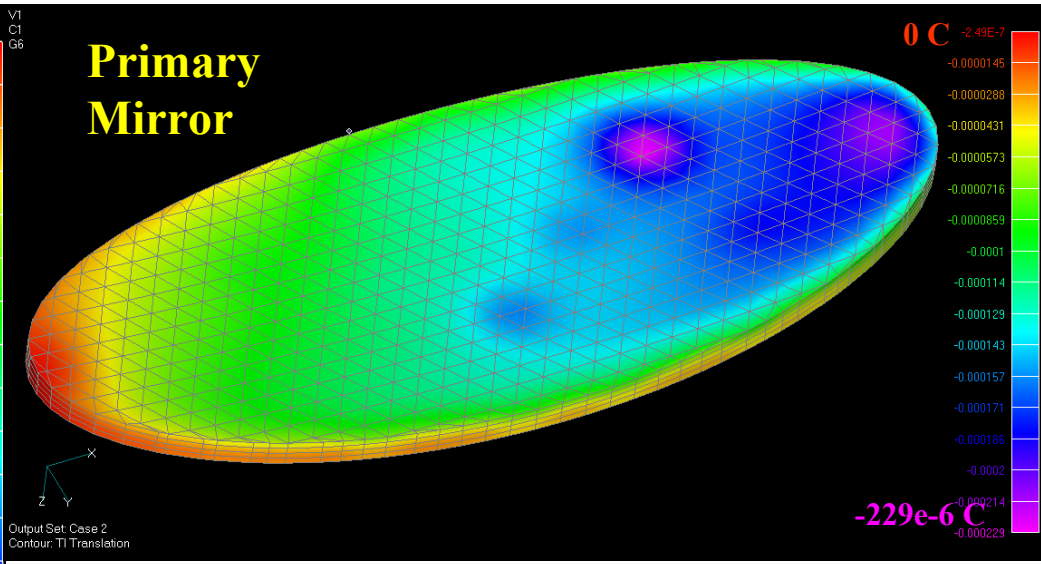
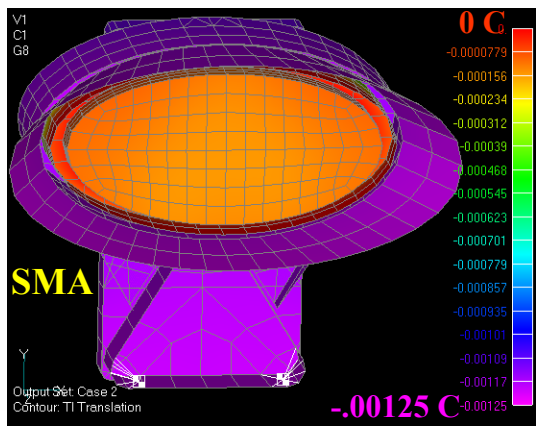
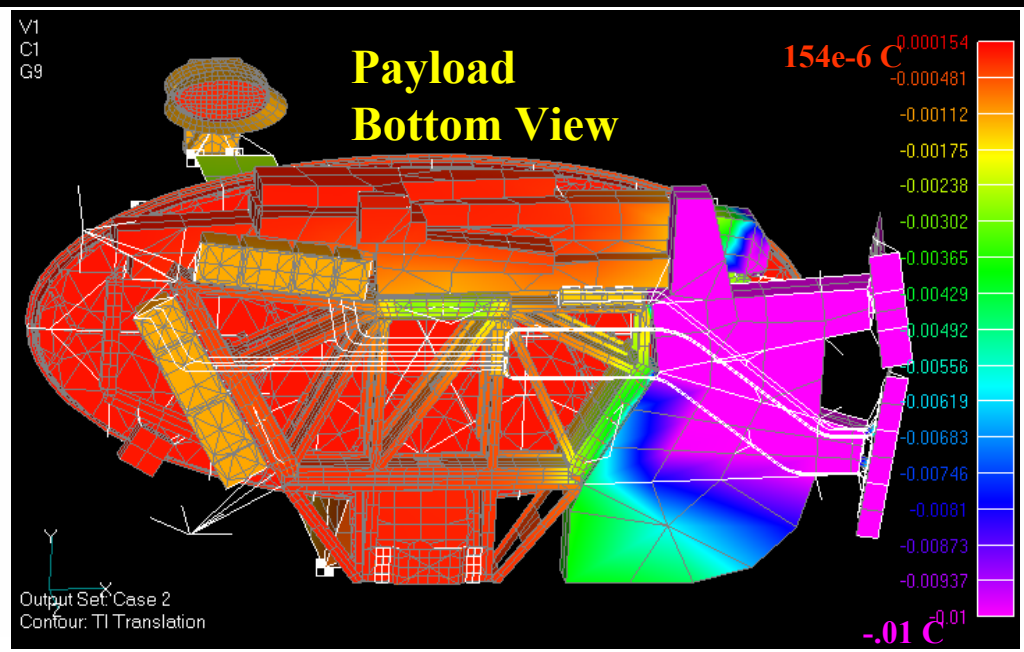
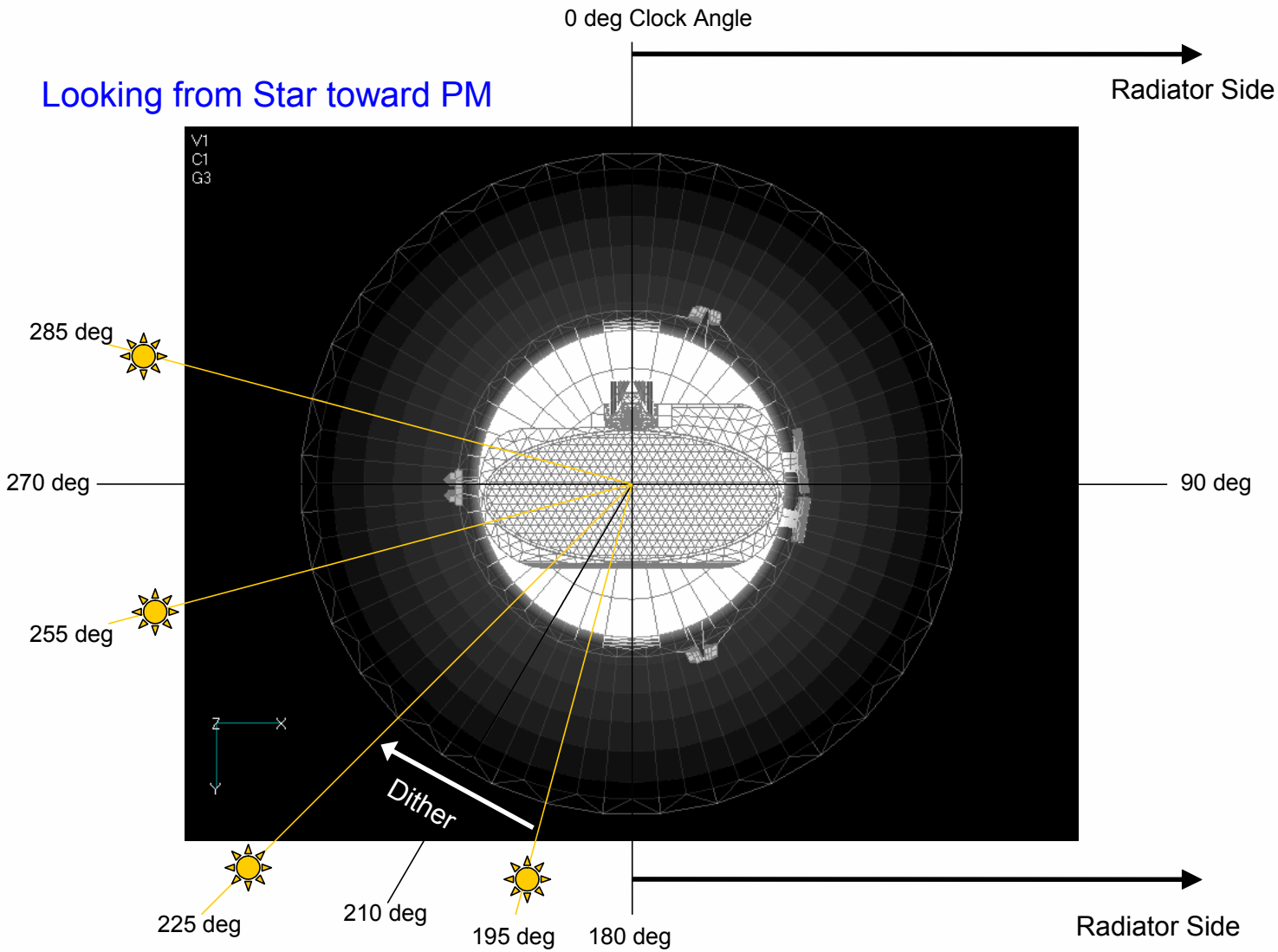




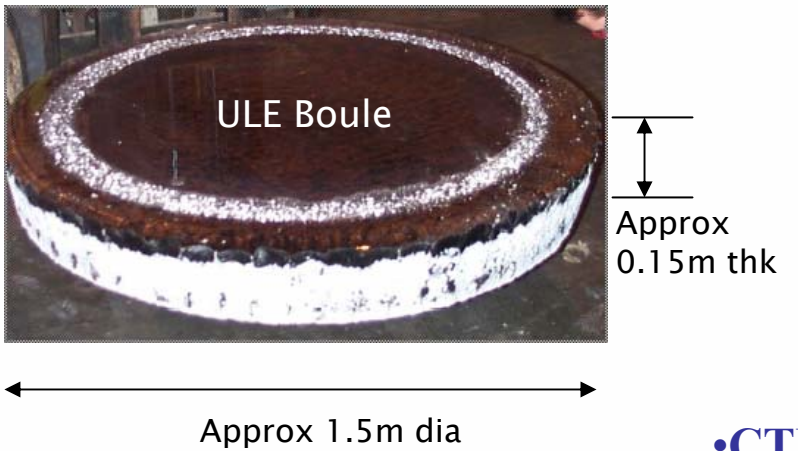




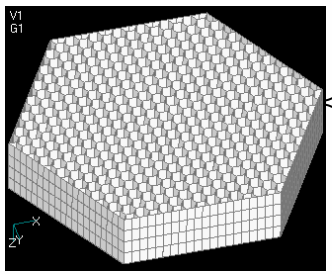
In-Orbit Performance with Thermal Disturbance from Dither Maneuver

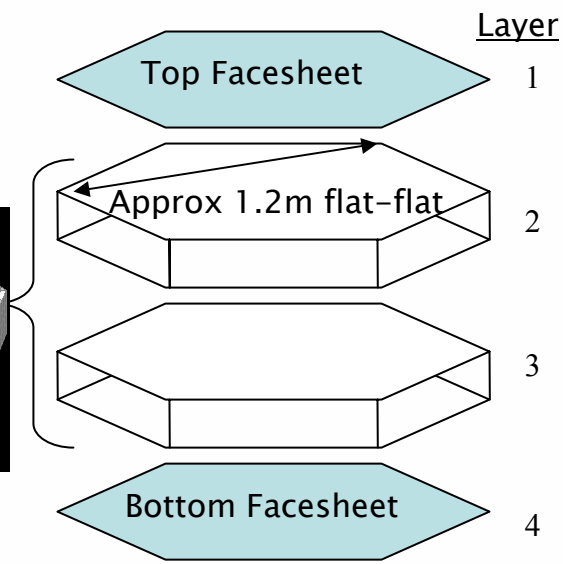


Monte-Carlo Study of Primary Mirror CTE Variation



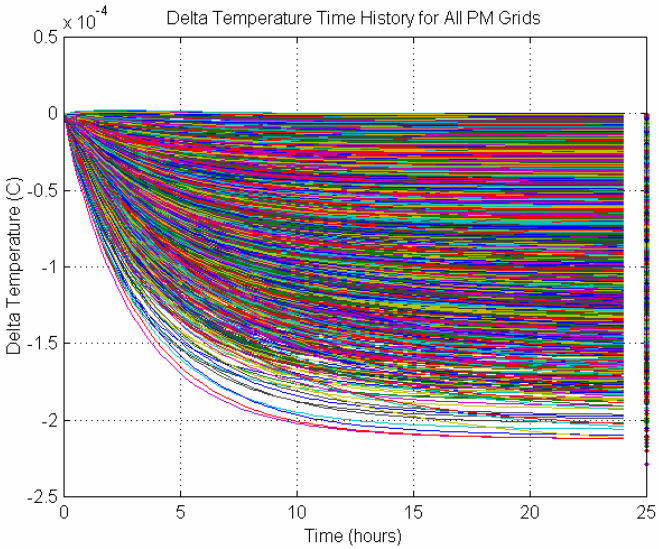
Core Segment:
Two Stacked, Sealed & Fused Boules

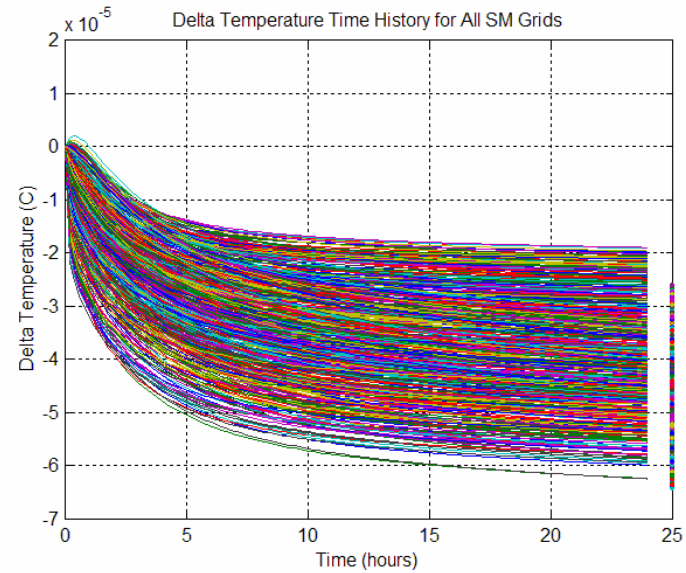


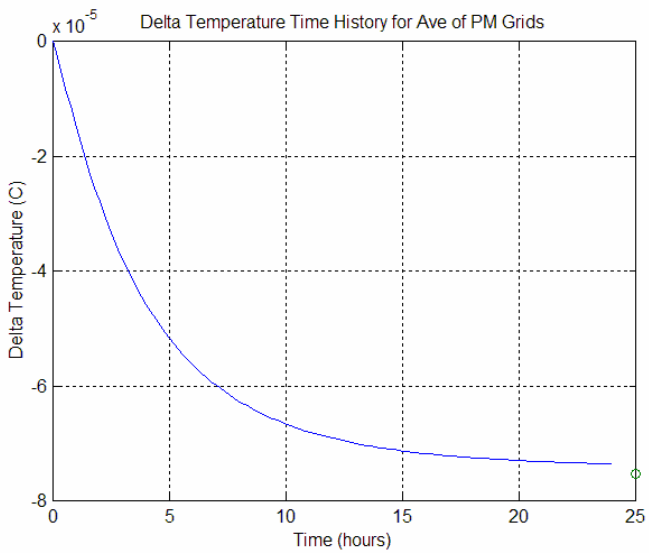


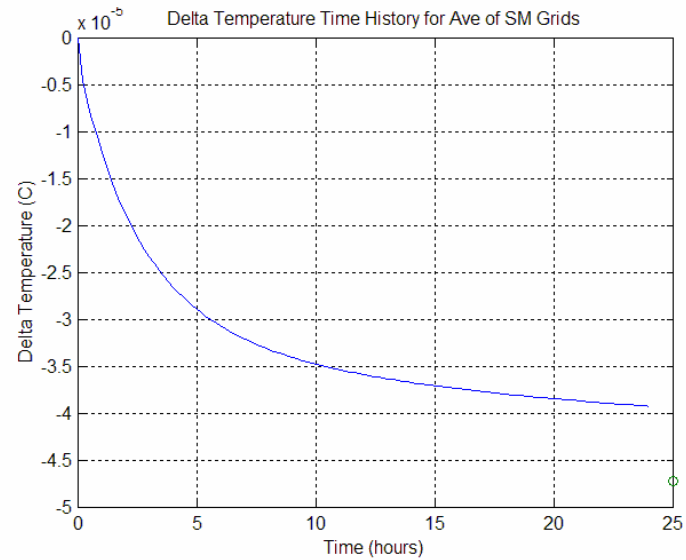
- **CTE was varied by region**
- **There are 92 regions used**
  - 4 layers x 23 segments
- **CTE variation functions used:**
  - **Bias** or piston
  - **Side to side** variation along x & y dir
  - **Radial** (in xy plane)
  - **Axial** (along z-dir)

Delta-Temps for 30 deg Dither (195-225, deg C)





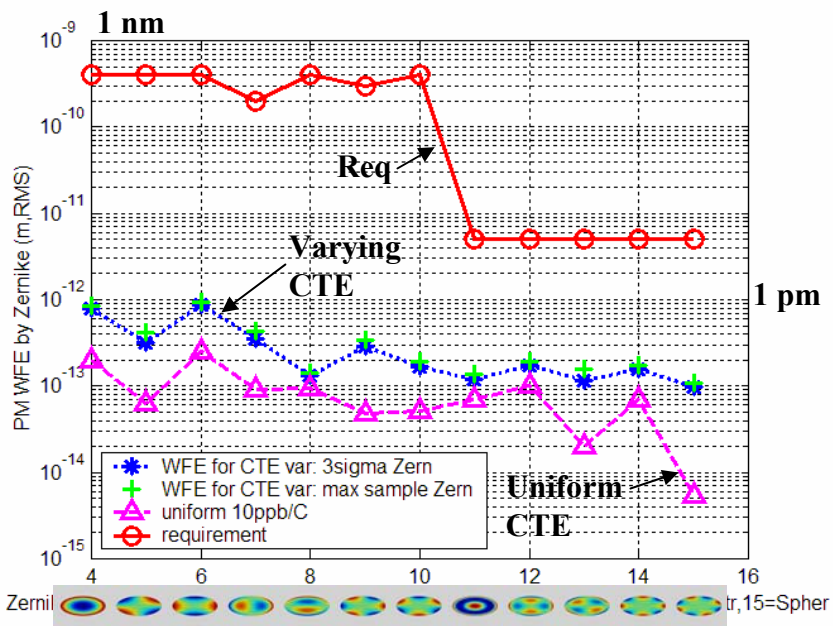




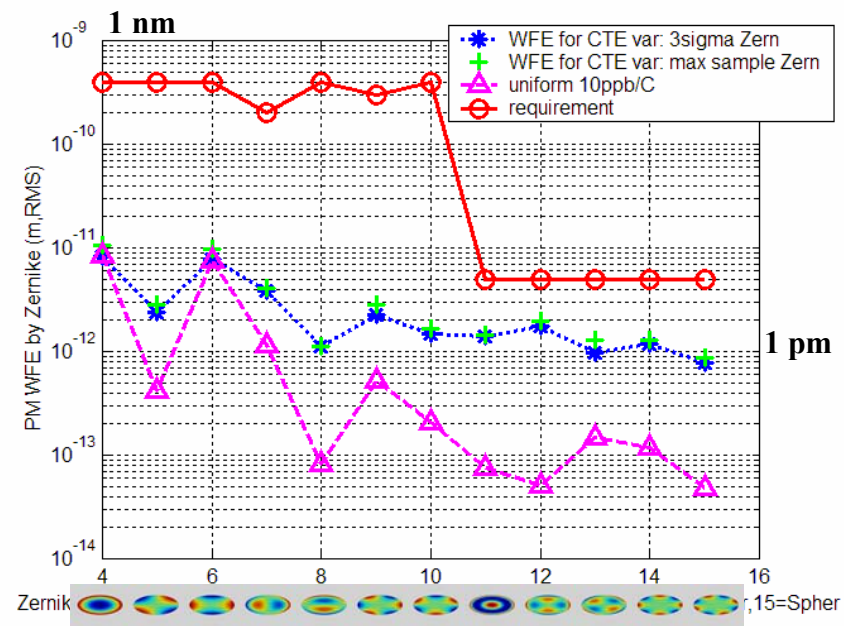
Monte-Carlo Study of Primary Mirror CTE Variation

Steady-State Dither Results Comparison

30 deg Dither (**255-285**)



30 deg Dither (**195-225**)

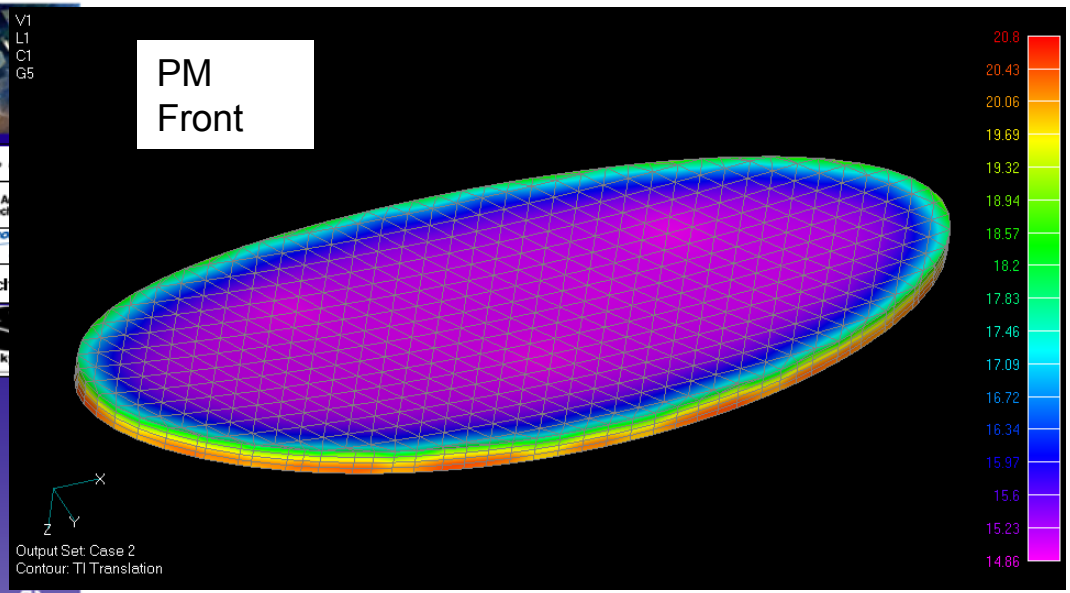


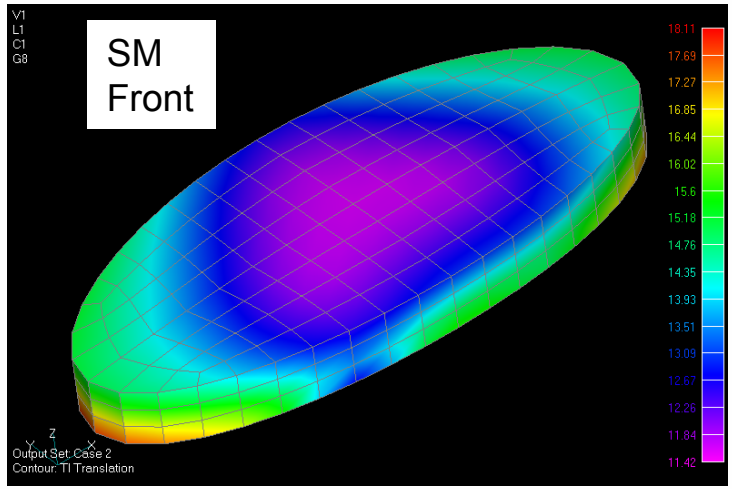
- **Current WFE performance is within error budget** (more conditions consid in future)

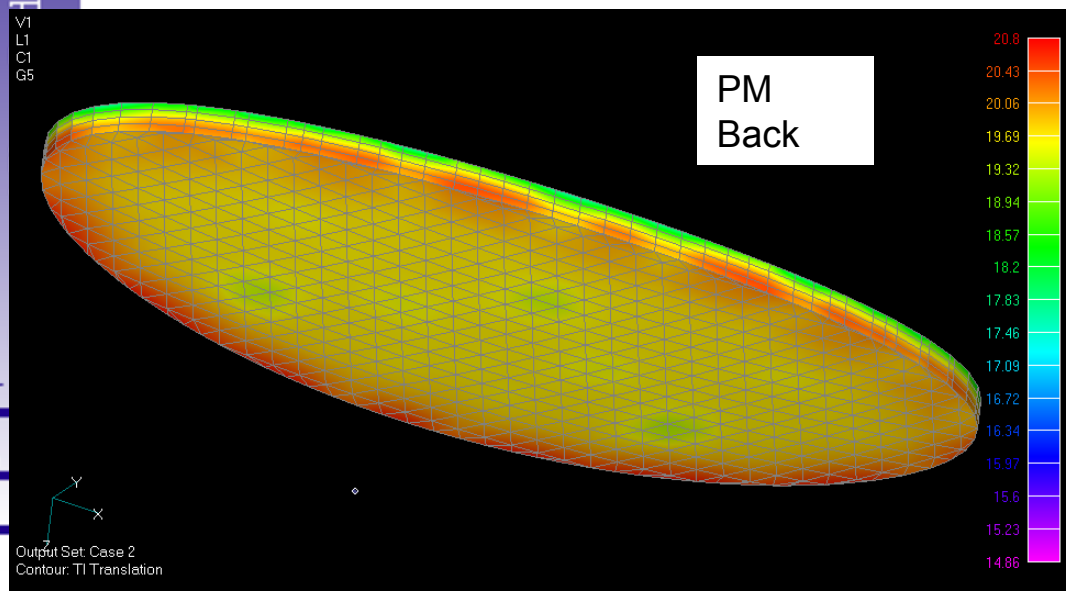
  Can be significantly improved with segment positioning based on measured CTEs
- **Need to consider CTE variability**: uniform CTE assumption is not conservative
- Can determine allowable **CTE tolerances** with this type of analysis

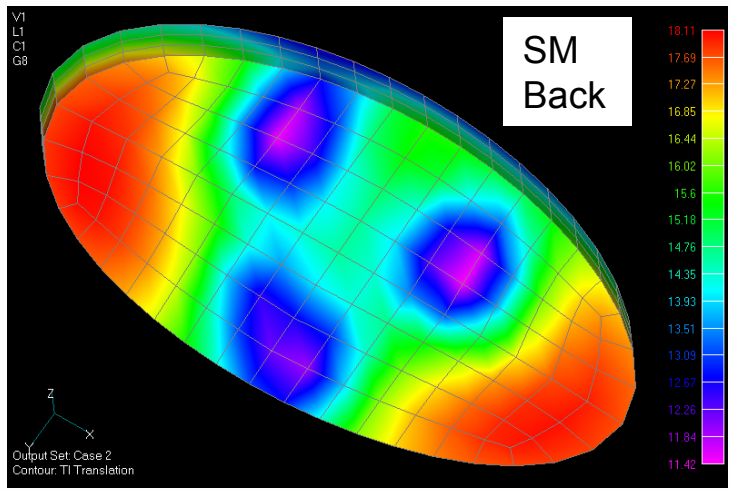
Primary & Secondary Mirror Temps for 285deg Sun Angle

Temps in deg C



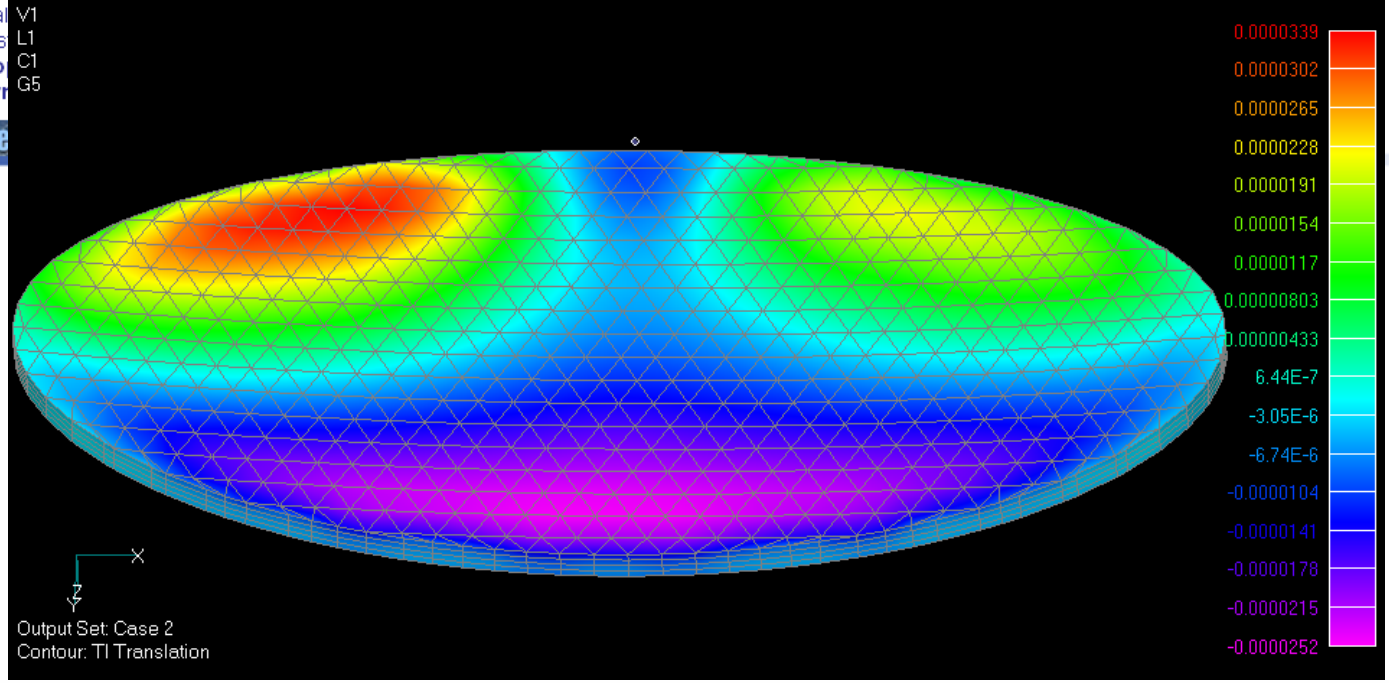






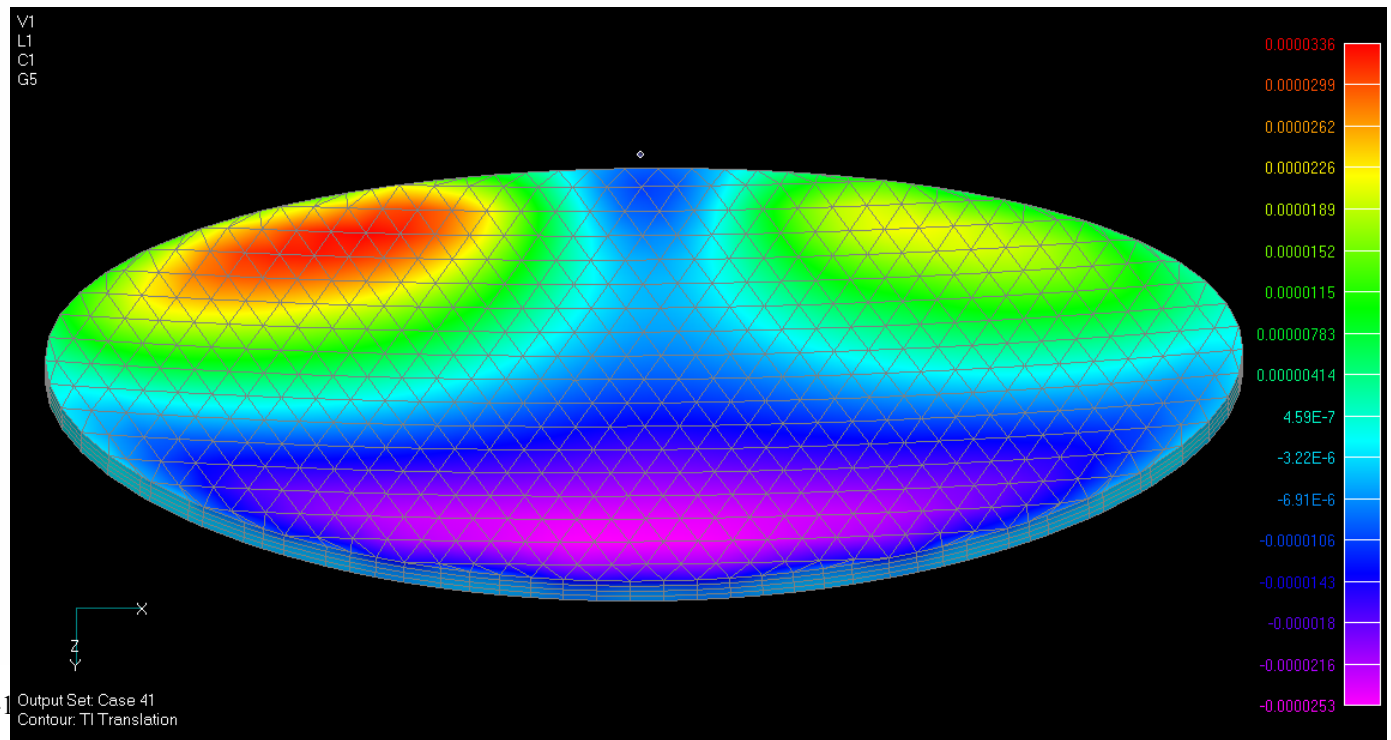
Delta Temp Contours

30 deg Dither (255 to 285 deg)



Steady-State

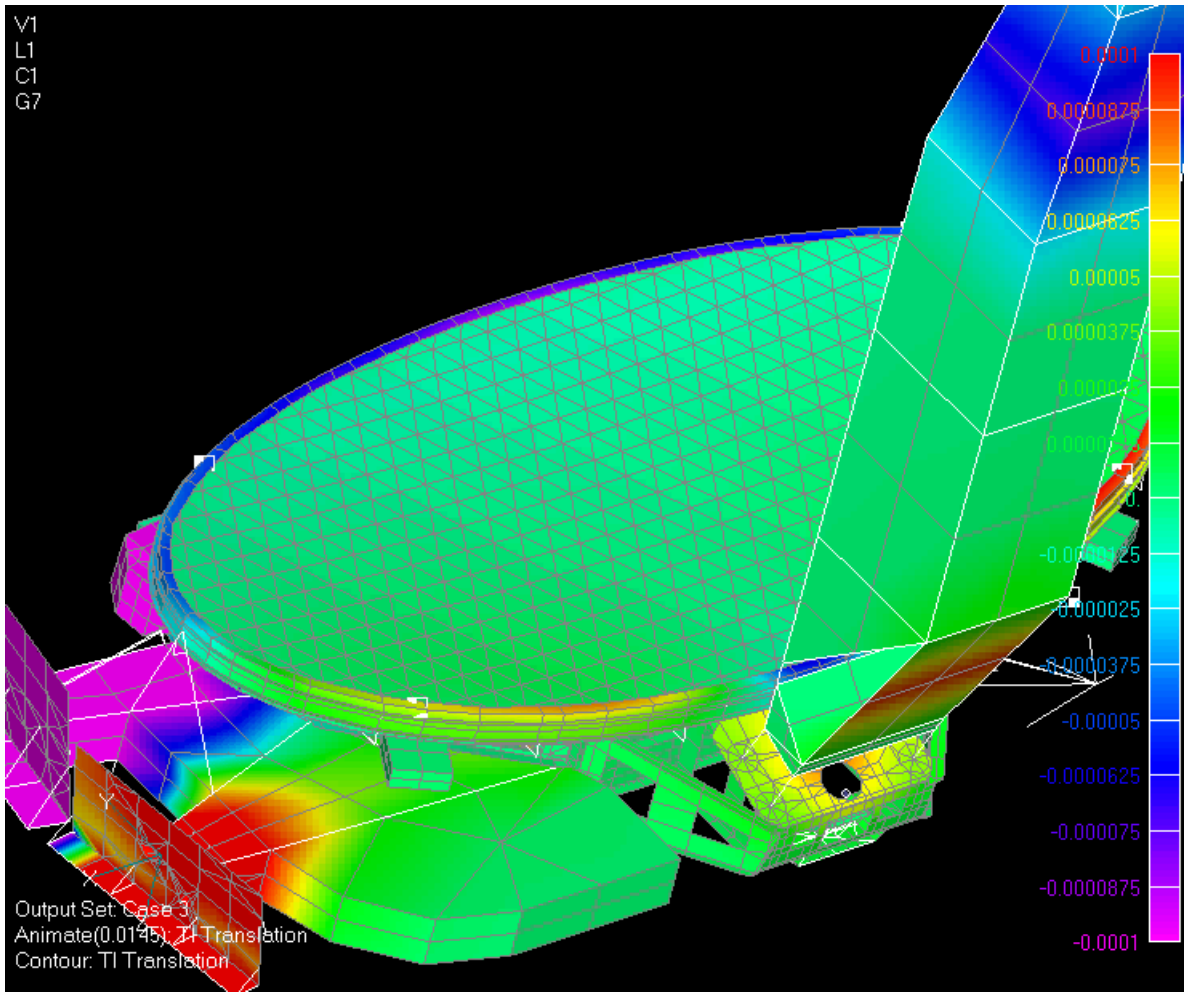
PM Front



Transient after 24 hrs

Click picture to run animation of Delta Temp Contour Change over Time

30 deg Dither (255 to 285)



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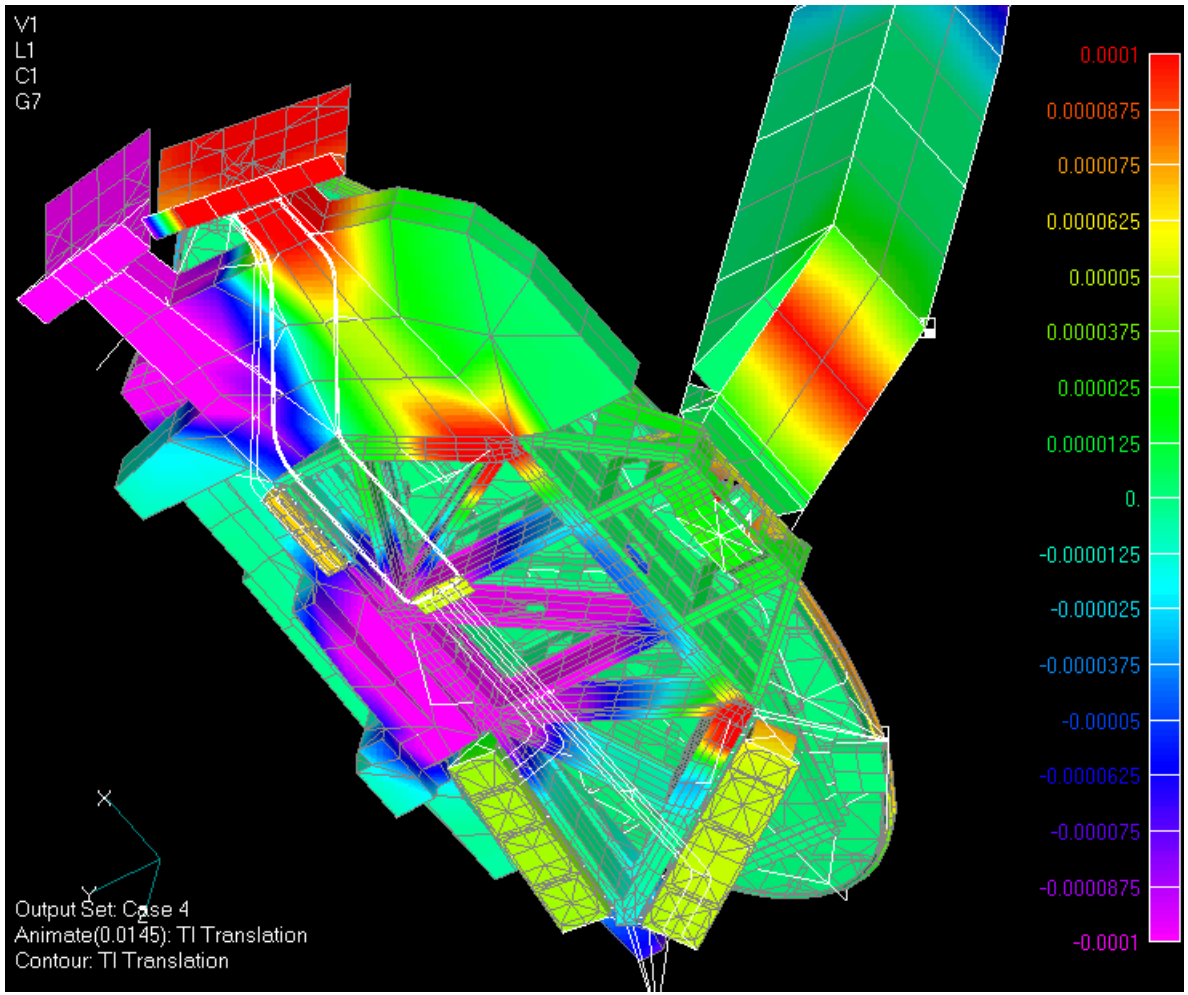
nightsky systems

Click picture to run animation of Delta Temp Contour Change over Time

30 deg Dither (255 to 285)



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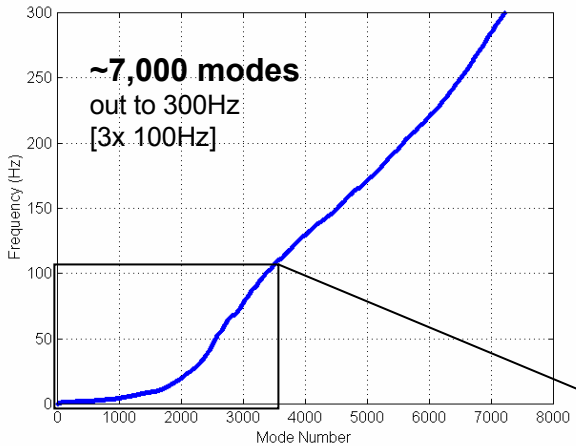
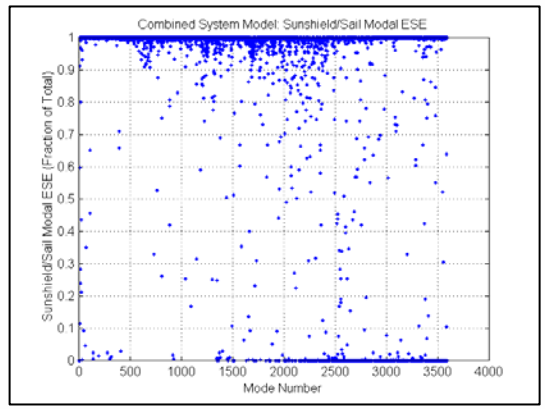
TPF Terrestrial Planet Finder

Combined System Normal Modes Used for Dynamic Response Analysis

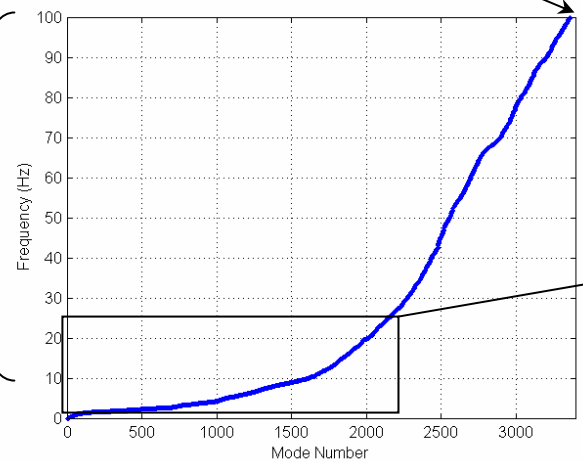
- Very high modal density, due to presence of sunshield and solar sail



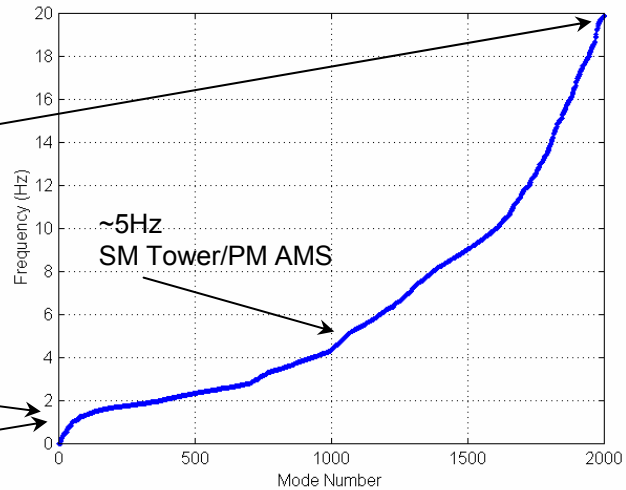
Fraction of Modal Strain Energy in Shield/Sail Assy



Response Freq Range of Interest for Jitter Analysis [10 – 100Hz]



~23Hz 1st Mounted PM Mode



~1.5Hz RWA Isolation Freq

~1Hz PSS/ Spacecraft Isolation Freq

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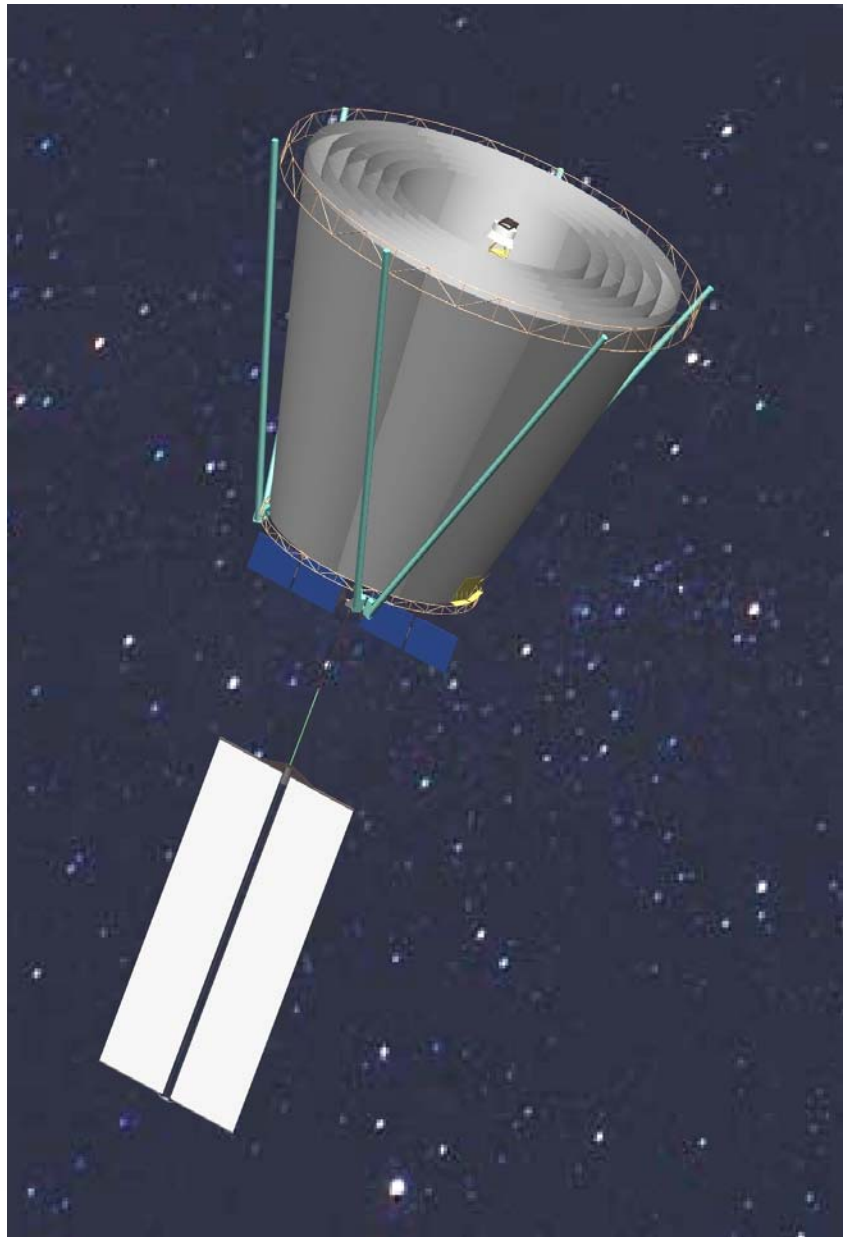
TPF Terrestrial Planet Finder

Primary Mirror (PM) Structural Models, Performance Results, & Future OTA Studies

Sandra Irish/GSFC

Contributors:
Ichung Weng/Swales Aerospace
Jeff Pattison/GSFC
Erik Benedetti/GSFC

11-12 July 2005



Executive Summary for the Primary Mirror (PM) Structural Models, Performance Results, & Future OTA Studies

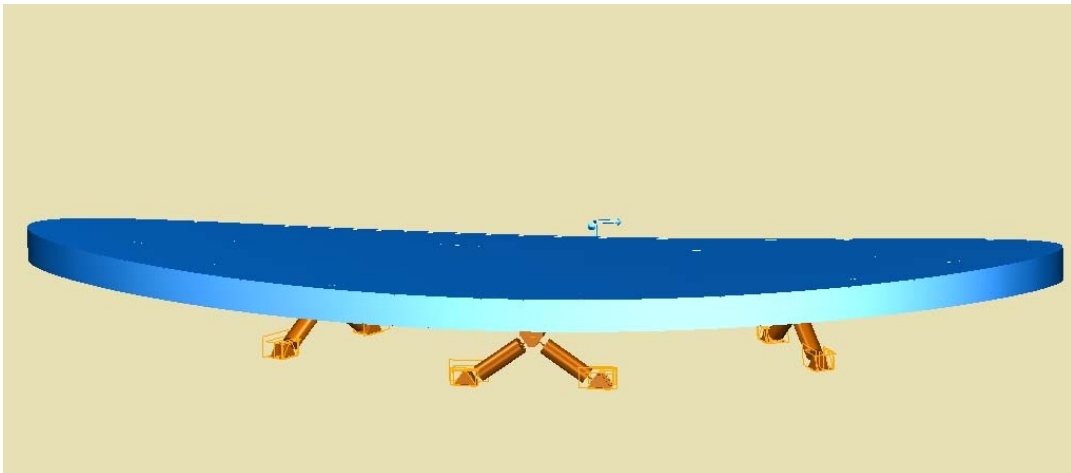
- **The following structural analyses have been performed for the OTA and the PM:**
  - Developed the OTA structural model for use in the TPFC integrated system performance analysis
    - OTA structural model was developed and provided to JPL. The model was used in integrated dynamics and thermal performance analysis. On-orbit dynamics is acceptable for active design, but marginal for passive design. Thermal stability was found to be acceptable.
    - Developed low, mid, and high fidelity structural models of the PM to be used for various structural analyses.
  - Acoustics analysis to estimate load to PM from Delta IV-H fairing
    - AutoSEA analysis performed and estimated a max load of 10 G applied to the PM due to either a metal or composite fairing
  - OTA and PM dynamics
    - First OTA free-free mode was found to be 7.1 Hz, due to tower bending. First mode of the PM with its mount was found to be 20.6 Hz.
  - PM gravity sag for ground testing concern
    - Maximum deflection of the PM with its mount due to 1 G loading applied perpendicular to the mirror was found to be .473 mm. Optical performance due to gravity sag was also predicted.
  - PM launch load stress analysis
    - The analysis showed that the PM has a negative margin of safety for the flight baseline 1 design concept. However, an option to obtain a positive margin of safety in the PM is to add weight of 414 kg as well as 8 launch locks. Still investigating additional design alternatives.

- **Future structural analyses for the FB1 design of the OTA and the PM include:**
  - Weight optimization of the PM, AMS, and SMA.
  - Sensitivity to PM mount design, location, and stiffness
  - PM Quilting Effects (PM deformation due to thermal loads)
  - Stiffness analysis of SM tower due to stiffness of hinges/latches
  - PM open-back versus closed-back structural/thermal analysis.

- **The results of all these structural analyses will help in developing the design concept for the PM and OTA for the flight baseline 2 analyses.**

Outline of Presentation

- Objectives
- PM Structural Models
- Gravity Sag
- Dynamics Analysis
- Launch Loads and Acoustics Analysis
- Stress Analysis due to Launch Loads
- Future PM and OTA Studies
- Conclusion



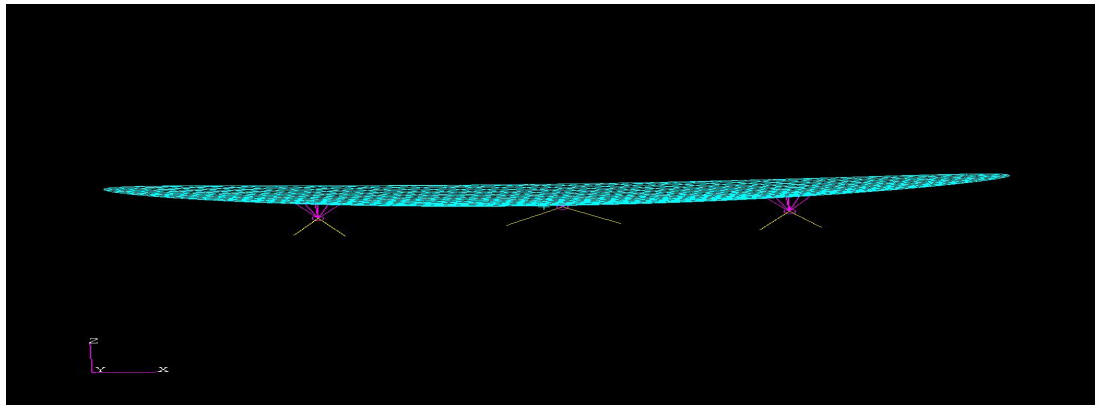
Objectives

Structural analyses are being performed to:

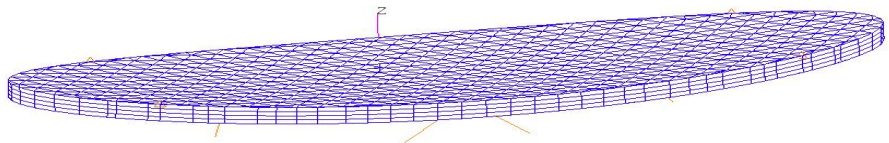
- Develop the OTA structural model for use in the TPFC integrated system performance analysis
- Show structural performance of the PM due to Delta IV-Heavy loads (both acoustics and liftoff)
- Show optical performance of the PM due to gravity sag and thermal loading
- Show that the OTA and PM have adequate stiffness to meet on-orbit performance and launch loading
- Develop weight optimized structural designs

PM Structural Models

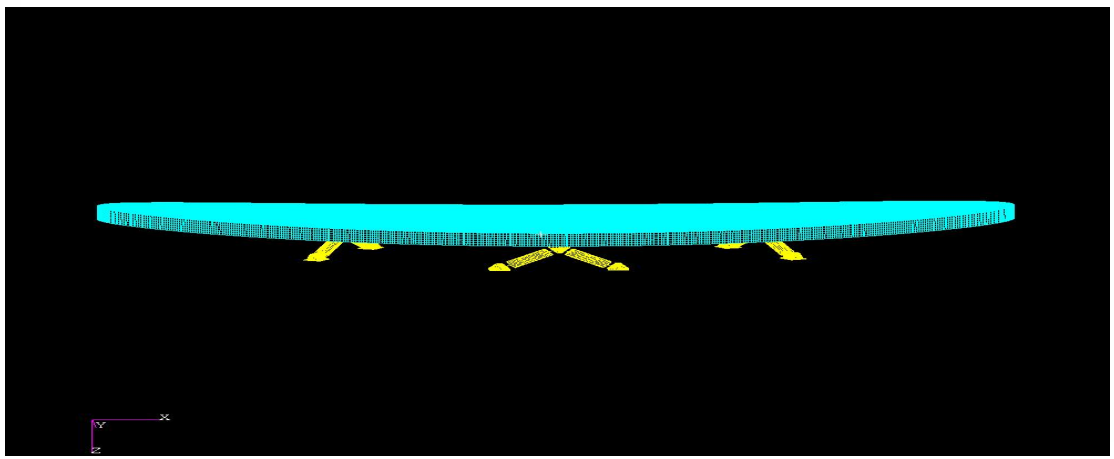
- PM Low-Fidelity Structural Model
  - Description: Flat plate model to represent PM and bar elements to represent mounts
  - Purpose: Acoustics analysis and trade studies



- PM Mid-Fidelity Structural Model
  - Description: Solid model to represent PM and bar and spring elements to represent mounts
  - Purpose: TPFC system dynamics and thermal analyses, and trade studies



- PM High-Fidelity Structural Model
  - Description: Detailed plate model that represents all core and mirror segment geometry and detailed bar and solid elements to represent the mounts
  - Purpose: PM gravity sag, stress analysis, weight optimization studies



PM High-Fidelity Structural Model: Model Overview

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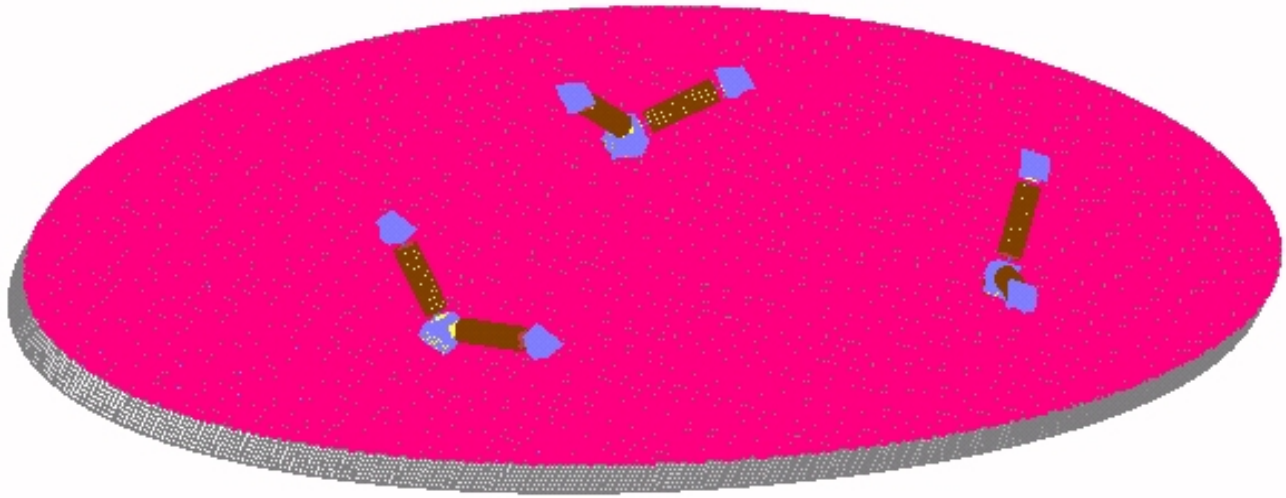
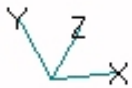
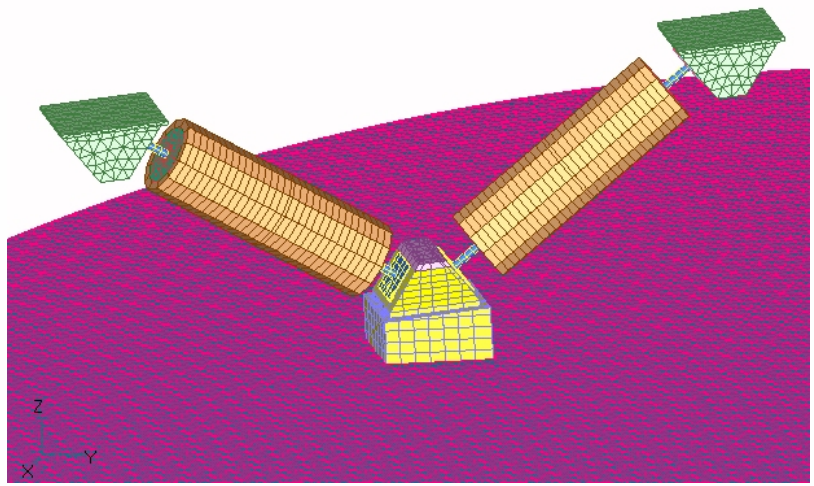




Sub-system	CBAR	CQUAD / CTRIA	CQUADR/ CTRIAR	CHEXA/ CPENTA/ CTETRA	RBE3
PM	0	285,472	0	0	0
Bipod	96	0	240	15,248	24
TOTAL	96	285,472	240	15,248	24

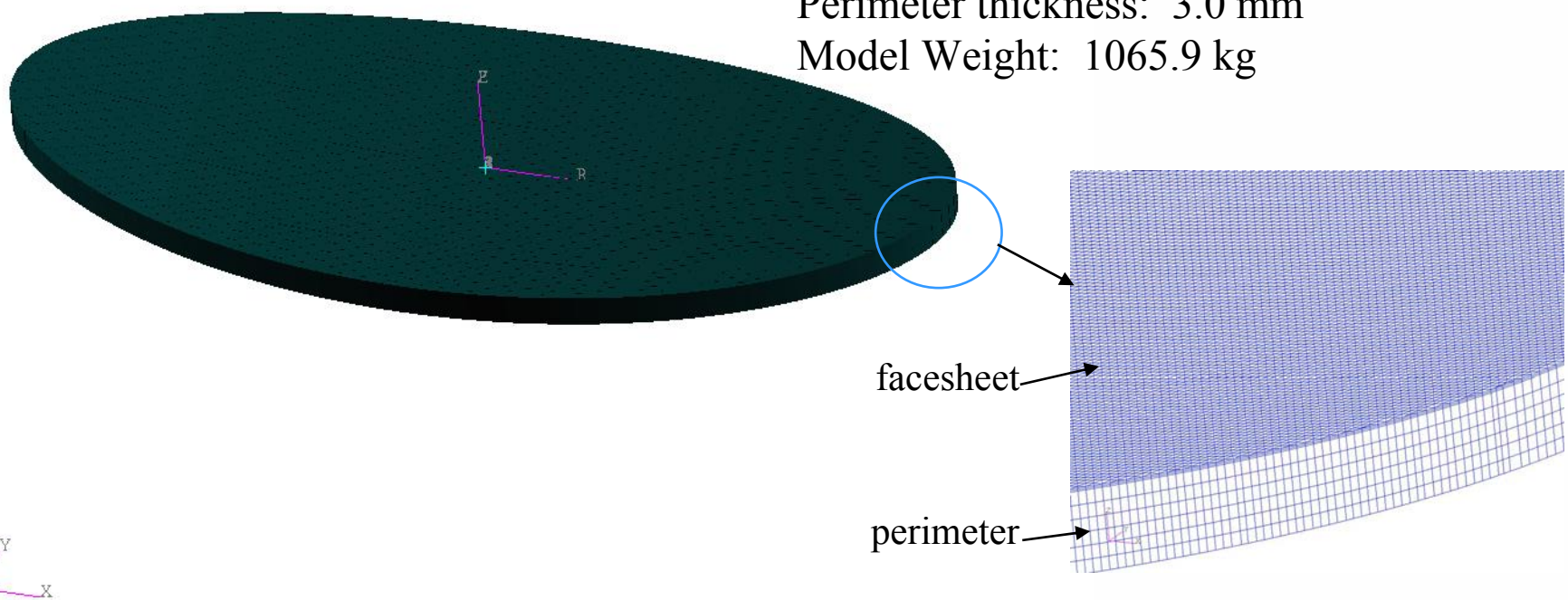
TOTAL ELEMENTS 301,080
TOTAL NODES 189,786



PM High-Fidelity Structural Model: PM Parameters

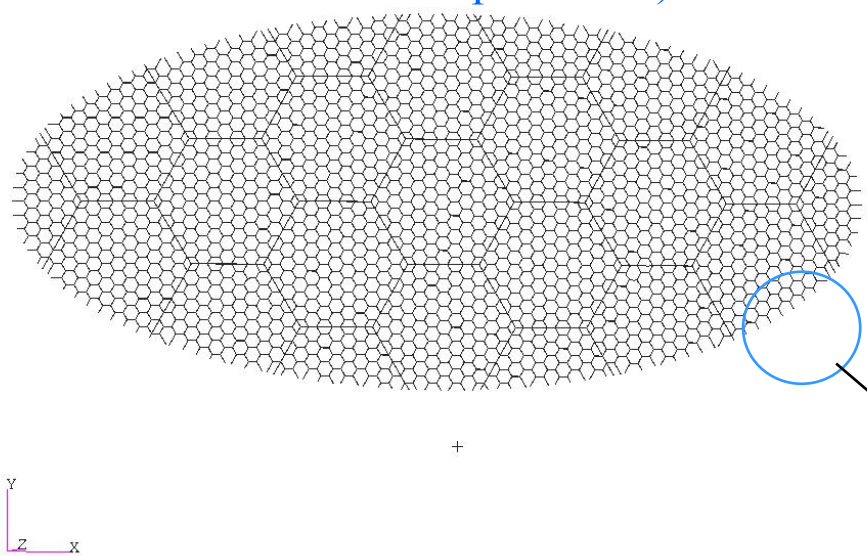
177196 grids
285472 elements
PM material is ULE.

Outer dimensions: 8.0 m x 3.5 m x .25 m
Facesheet thickness: 7.3 mm
Backsheet thickness: 7.3 mm
Top of core thickness: 3.0 mm
Core thickness: 1.5 mm
Top of segment struts thickness: 6.0 mm
Segment struts thickness: 3.0 mm
Perimeter thickness: 3.0 mm
Model Weight: 1065.9 kg

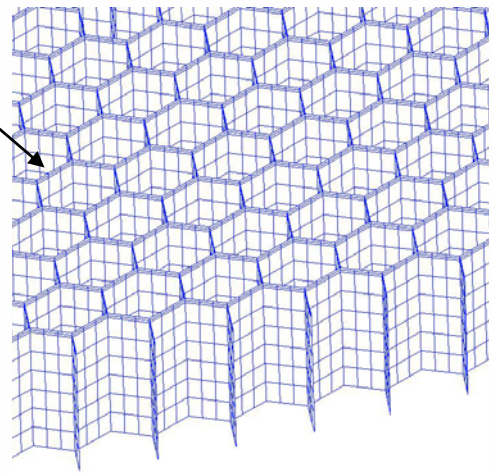


PM High-Fidelity Structural Model: PM Hex Core

Core
(shown with segment struts
and without perimeter)

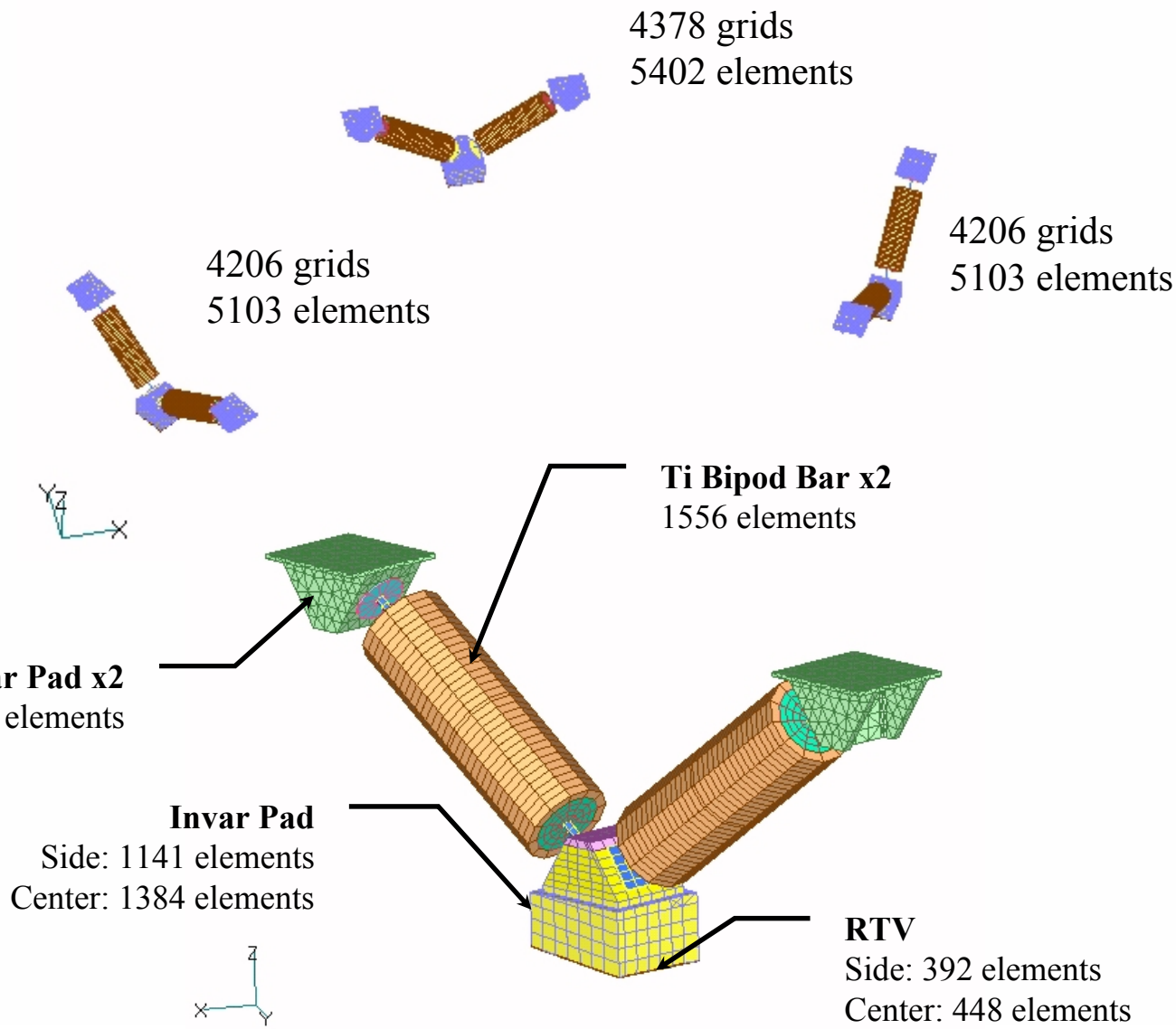


Hex Core
Wall Thickness is 1.5 mm



PM High-Fidelity Structural Model: Mount Parameters

Total:
12790 grids
15608 elements



PM High-Fidelity Structural Model: Weight

TPFC Primary Mirror and Bipod Assembly FEM Weight Breakdown			
Component	**Material**	**FEM Weight (Kg)**	**Solid Model Weight* (Kg)**
Primary Mirror Optic	ULE	1065.94	1066.00
Bipod Pads	Invar	127.95	117.50
Bipod Strut	Titanium	67.38	72.30
Total		**1261.27**	**1255.80**

PM Gravity Sag due to 1 G Gravity Loading in Z direction

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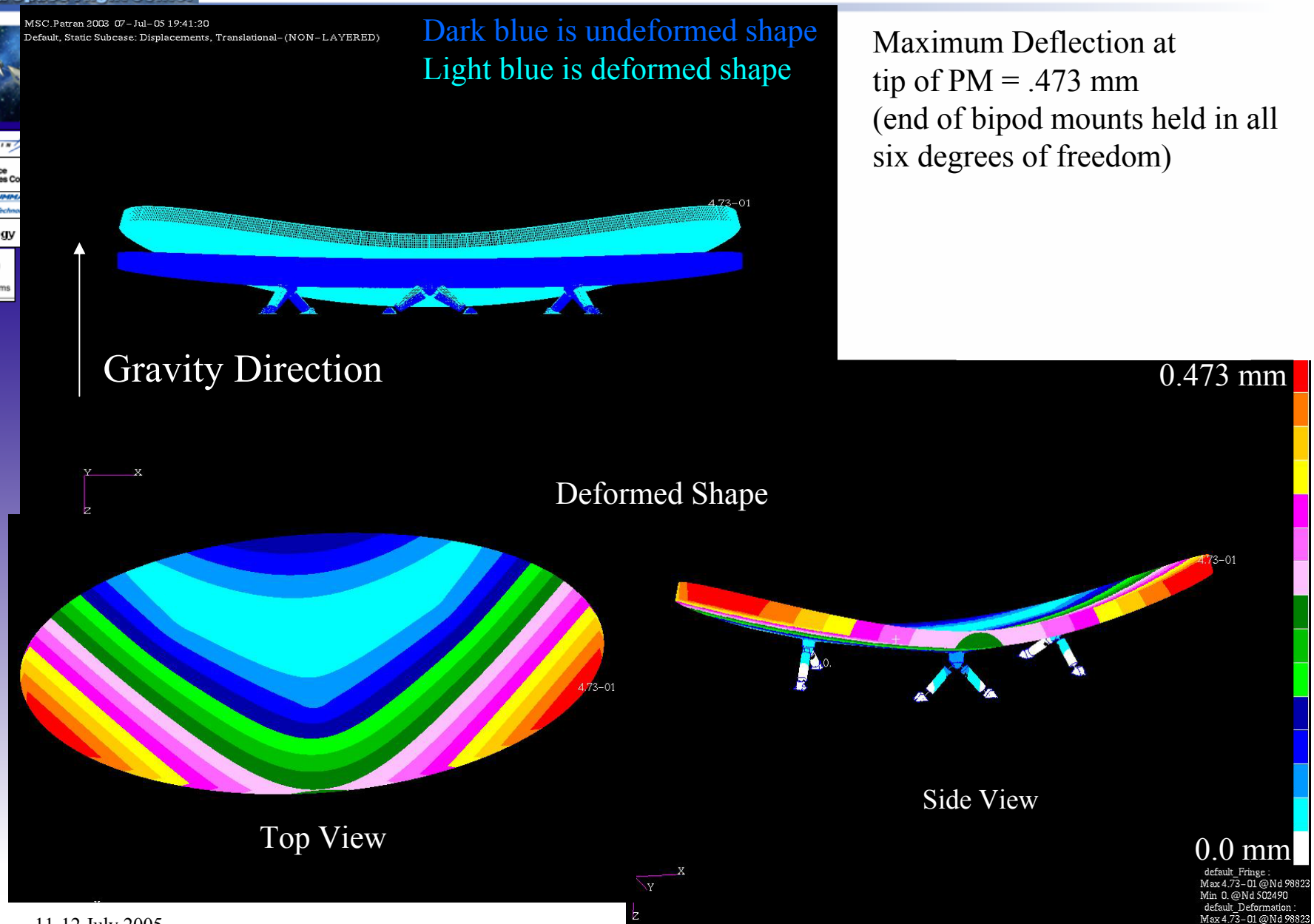
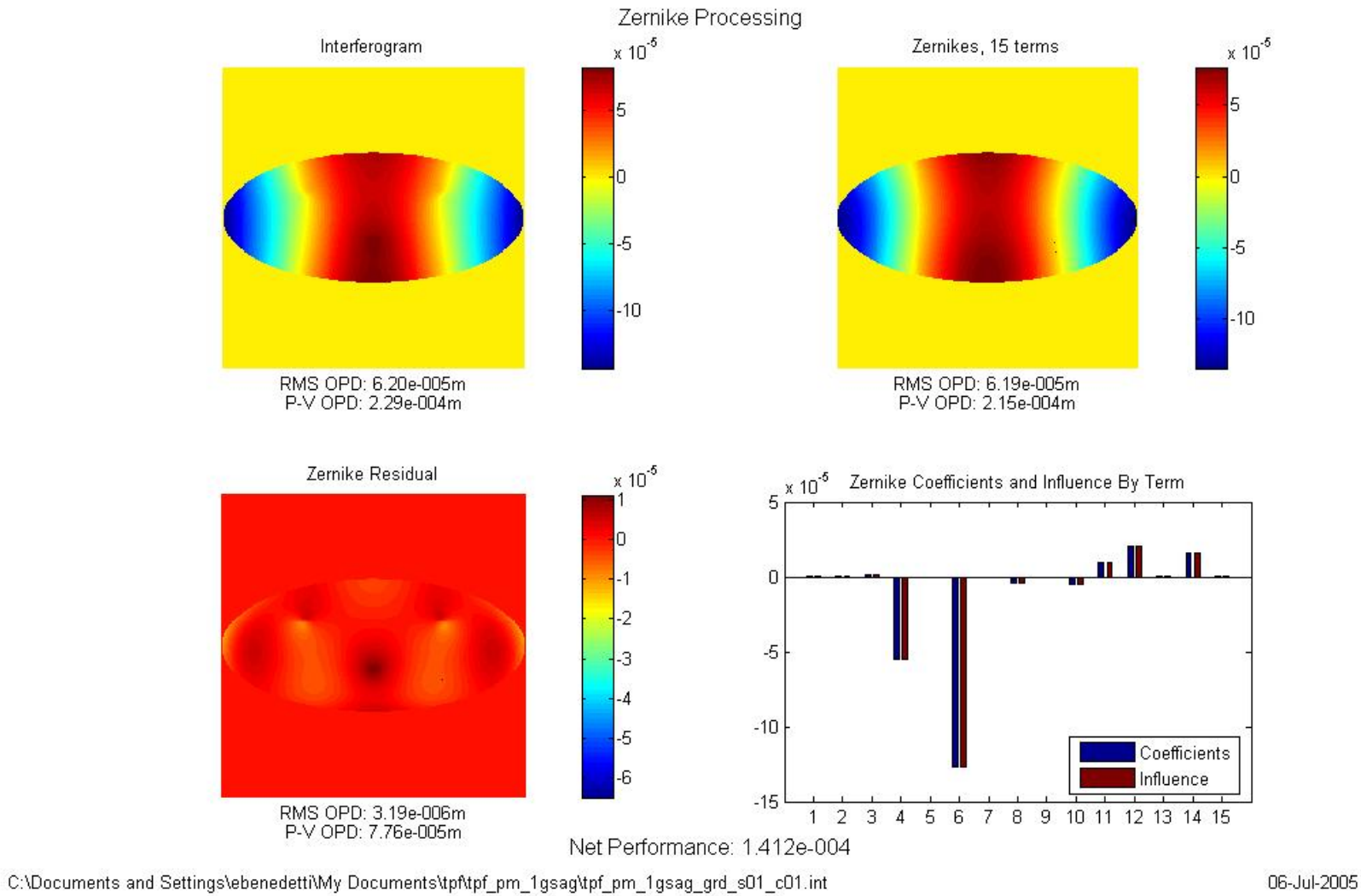


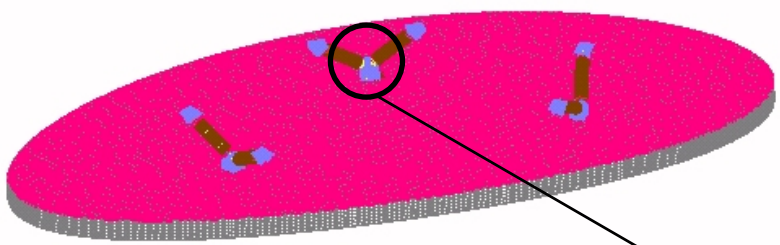
Maximum Deflection at tip of PM = .473 mm (end of bipod mounts held in all six degrees of freedom)

PM Optical Performance due to 1 G Gravity Loading in Z direction



PM Dynamics Analysis

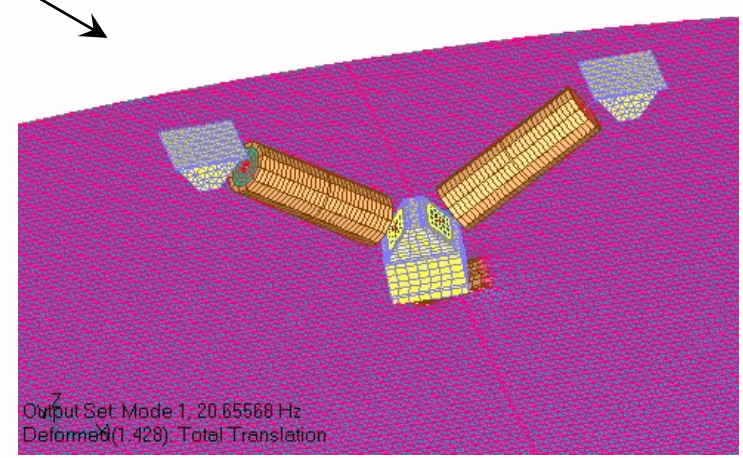
PM Bipod model was held at base of Invar pad.
First mode is 20.65 Hz (RTV thickness 1 mm)



Mode 1: 20.65 Hz
(brown is undeformed)

Baseline Design

Mode	Frequency (Hz)
1	20.65
2	21.14
3	29.56



Launch Loads

PM stress analysis used Delta IV-Heavy load factors.

- Quasi-static load:
  - 6G in X & .5G in -Z
  - 6G in X & .5G in Y
- Acoustics load: 10G in Z (acoustics analysis performed to obtain this load level)

Materials	ULE	RTV	Invar	Titanium (Ti-6Al-4V)
Allowable	15.2 Mpa/2200 psi (tensile)	2.1 Mpa/300 psi (tensile) 1.2 Mpa/173 psi (shear)	461.9 Mpa/67 ksi (ultimate) 262.0 Mpa/38 ksi (yield) 96.5 Mpa/14 ksi (microyield, 1ppm plastic deformation)	896.3 Mpa/130 ksi (ultimate) 827.4 Mpa/120 ksi (yield)
Source for Allowable	ITT TDM baseline	ITT TDM baseline	Daniel Polis NASA code 541	MIL-HBK-5H
Factor of Safety (FS)	3.0 5.0 (analysis only)	2.0	1.4 (ultimate) 1.25 (yield)	1.4 (ultimate) 1.25 (yield)
Source for FS	NASA-STD-5001	NASA-STD-5001	NASA-STD-5001	NASA-STD-5001

PM Stress Analysis: Flight Baseline 1 Results

Baseline Design

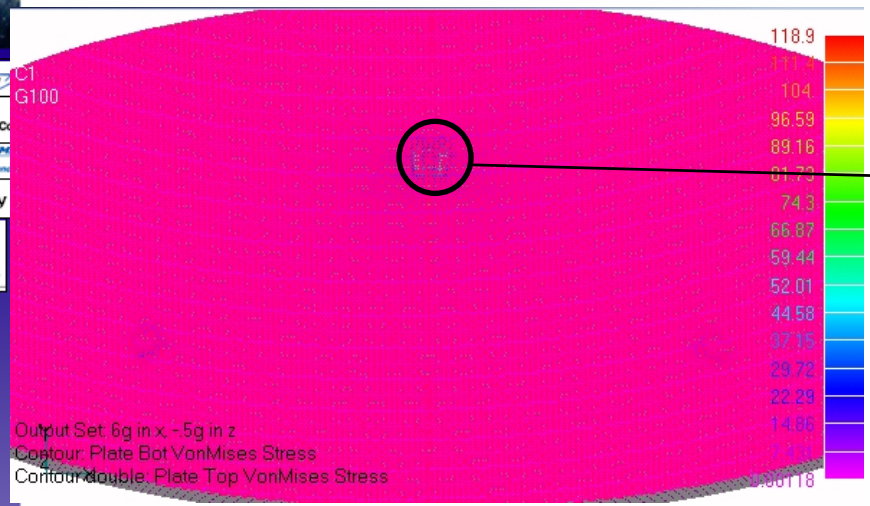
Component	Peak Stress (Mpa/ksi) Quasi-static Load (6 G in X, .5 G Z) Acoustic Load (10 G in Z)	Margins of Safety
PM ULE	151.8/22.02 66.71/9.68	**-.97** **-.92**
RTV	20.64 / 2.99 (tensile) 6.16/.89 (tensile)	**-.95** **-.83**
Ti bar	403.5/58.5 469.4/68.08	.59 (ultimate) / .64 (yield) .36 (ultimate) / .41 (yield)
Invar Mount	50.52 / 7.33 70.47 / 10.22	5.53 (ultimate) / 3.15 (yield) 3.68 (ultimate) / 1.97 (yield)

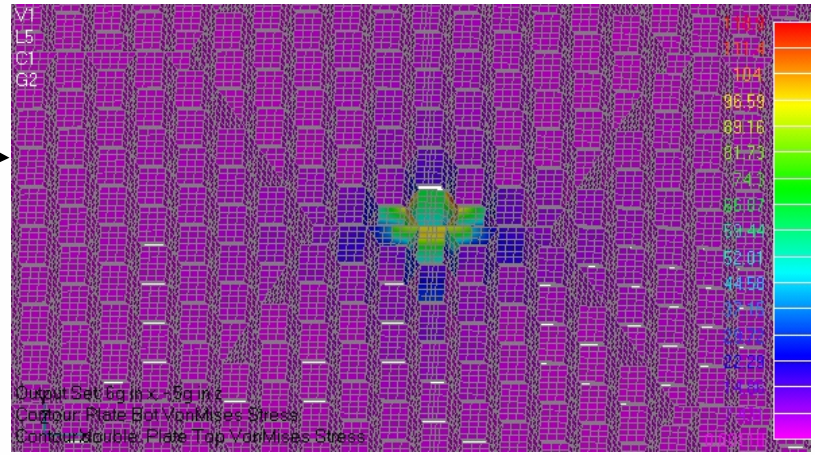
Note:
1. PM/Bipod structural model (baseline design) weights 1261.4 kg comparing 1255.8 kg of solid model.
2. Margins for Invar are based on nominal ultimate/yield allowable.

PM Stress Analysis: Flight Baseline 1 Results

6G in X & .5G in -Z

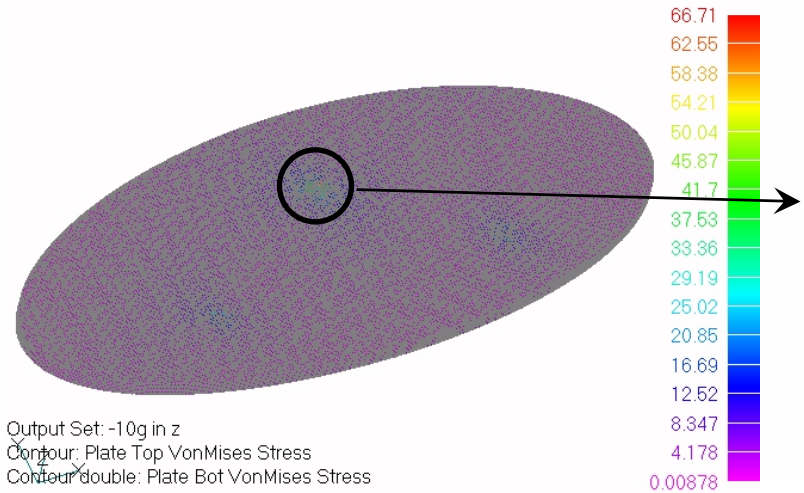
151.8 Mpa = 22.02 ksi

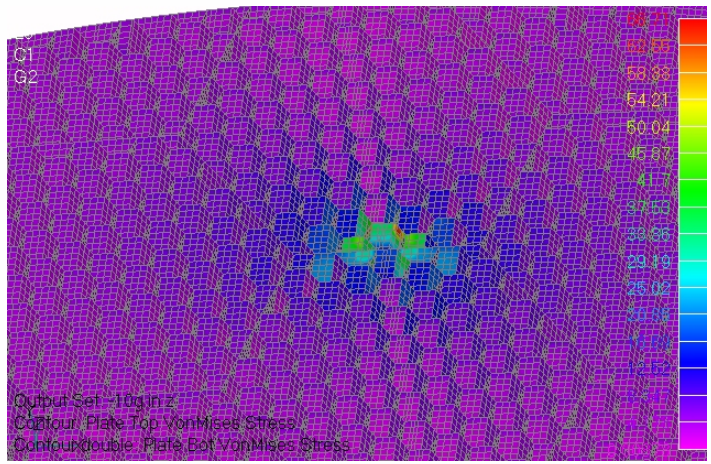




10G in -Z

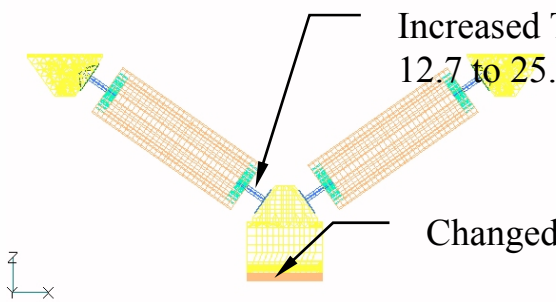
66.71 Mpa = 9.68 ksi





PM Stress Analysis: Mod 5 to Flight Baseline 1 Design

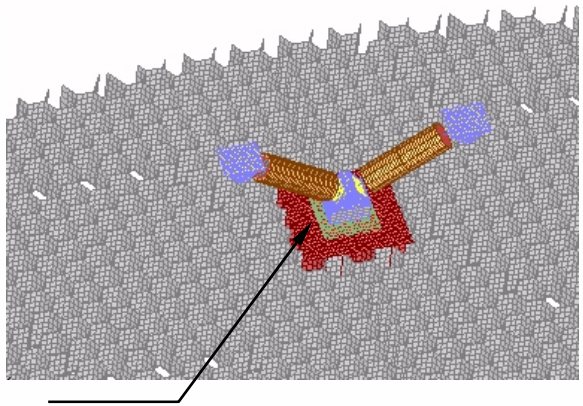
Mod. 5 (best case from previous analysis) :



Increased Ti bar diameter from 12.7 to 25.4 mm

Changed RTV to Invar

Increased PM wall thickness to 14.6mm in red colored area 18.5”x19.5” (included 9.8”x10.2” PM mounted area).

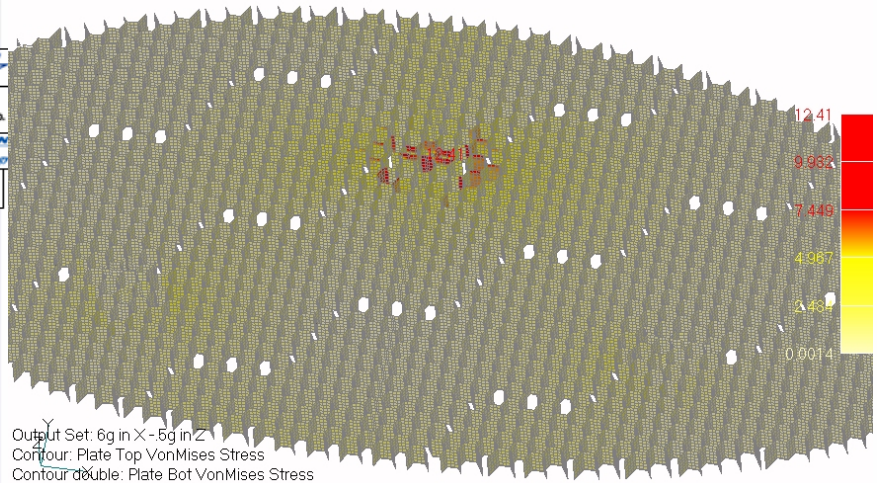


Configuration	Δ Weigh (kg)	PM Stress Quasi-static (MS) Acoustic (MS) (Mpa/ksi)	RTV stress Quasi-static (MS) Acoustic (MS) (Mpa/ksi)	Ti bar stress Quasi-static (MS) Acoustic (MS) (Mpa/ksi)	Invar Mount stress Quasi-static (MS) Acoustic (MS) (Mpa/ksi)
Baseline design	-	151.8/22.02 **(-.97)** 66.71/9.68 **(-.92)**	20.64 / 2.99 **(-.95)** 6.16/.89 (tensile) **(-.83)**	403.5/58.5 (.59/.64) 469.4/68.08 (.36/.41)	50.52 / 7.33 (5.53/3.15) 70.47 / 10.22 (3.68/1.97)
Modification 5	+122.3	13.04/1.89 **(-.61)** 17.14/2.49 **(-.71)**	N/A	98.73/14.32 (5.48/5.7) 131.9/19.13(3.85/4.02)	73.33 / 10.46 (3.57/1.91) 94.32 / 13.68 (2.50/1.22)

PM Stress Analysis: Mod 5 to Flight Baseline 1 Design

6G in X & .5G in -Z

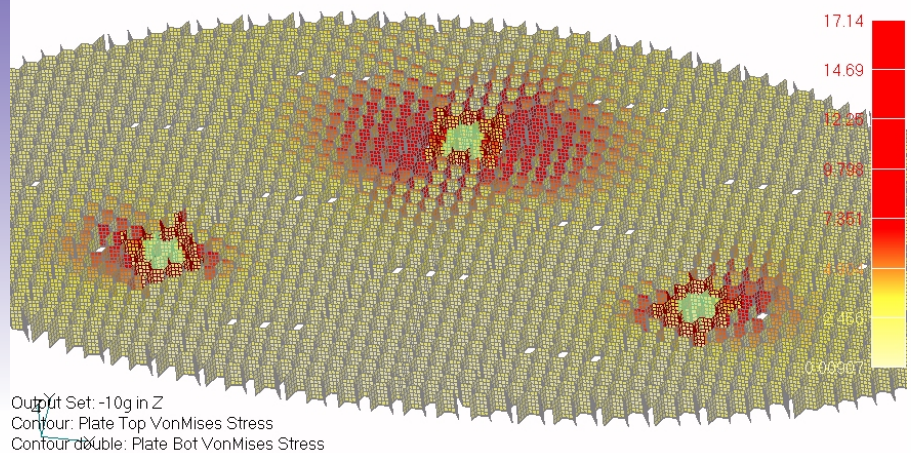
12.4 Mpa in Core



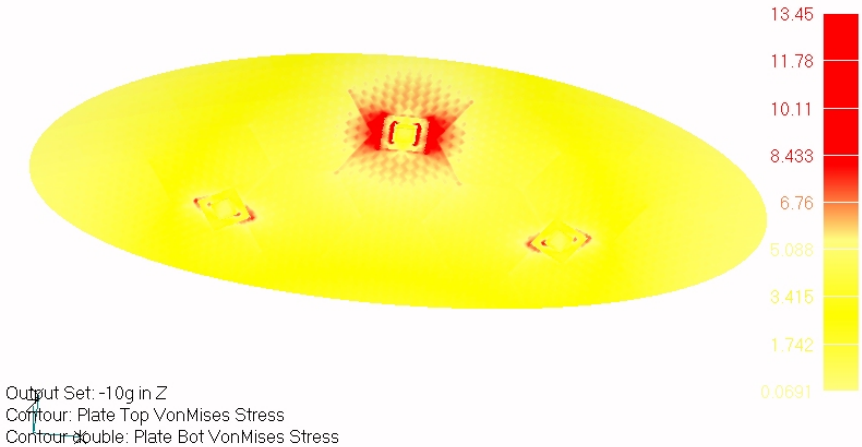
13.0 Mpa in back facesheet

10G in -Z

17.1 Mpa in Core



13.4 Mpa in back facesheet

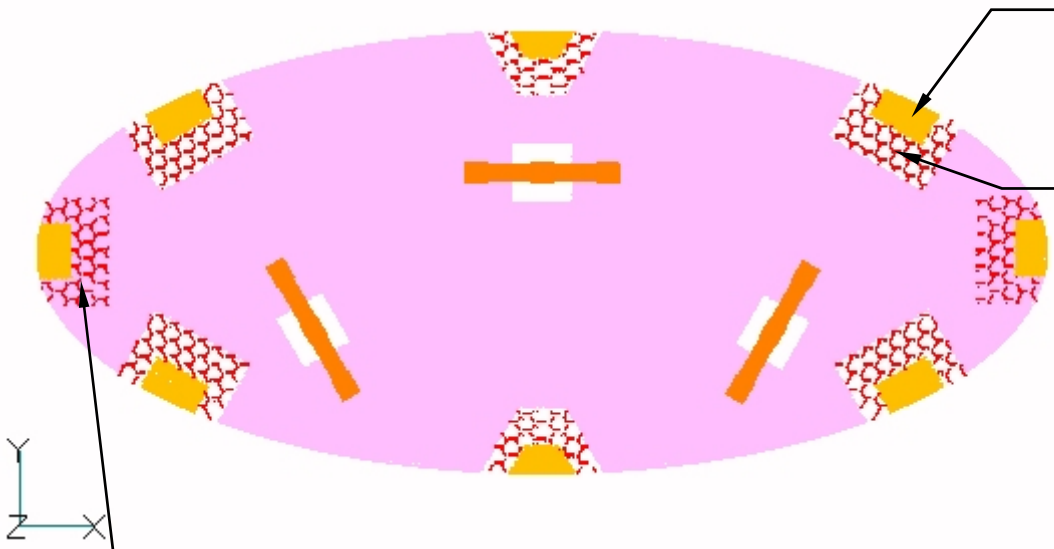


PM Stress Analysis

- PM Stress Analysis Peer Review was held to discuss possible solutions to achieve positive margin of safety in the PM for launch loads.
- Comments and suggestions include:
  - Category 1: Modifications to PM and mount that do not require major design changes to the OTA or other TPFC hardware
    - Perform a trade study to look at bipod angle (need to reduce moment into PM)
    - Change shape of Invar mount pad, ie. Hex, shorter and tapered at edges
    - When including additional stiffness in the PM behind the mount region, apply a gradual thickness change as you move out from center of mount area
  - Category 2: Modifications that would require major design changes to the OTA or other TPFC hardware (possible changes for Flight Baseline 2 design)
    - Perform a trade study to determine optimal mount locations and bipod angle, also don't rule out a 4-pt mount
    - Adding launch locks (see next slide for details), try center launch lock
    - Look into stronger adhesive (possible affect to optical performance)
    - Consider alternate manufacturing process for ULE at mount area

PM Stress Analysis: Modification to Improve Design (Mod 5-8)

Mod 5-8 includes 414 kg of additional weight and 8 launch locks.



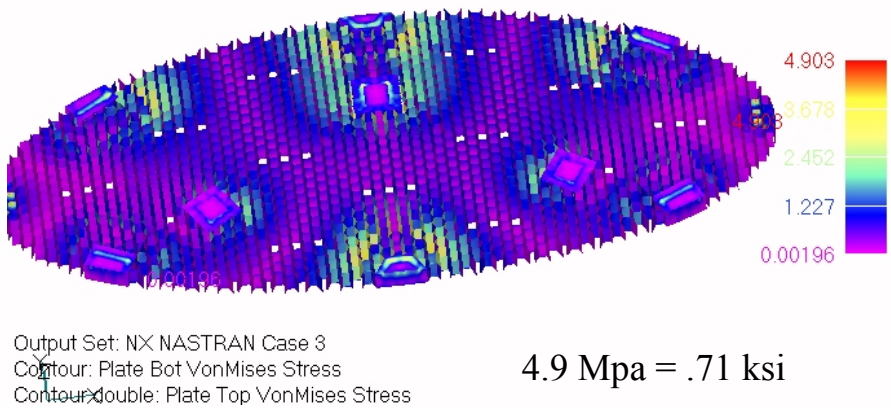
479 x 277mm (18.8” x 10.9”). Wall thickness is 42mm (include both side facesheet)

870 x 583mm (34.2” x 22.9”) (exclude 479 x 277 mm area). Core thickness is 6 mm. Both side facesheet thickness is 7.3mm.

867 x 582mm (34.1” x 22.9”). Core thickness is 4 mm. Back facesheet thickness is 5 mm. Front facesheet is 7.3 mm.

10G in -Z

Stress in PM Core



4.9 Mpa = .71 ksi

Future PM and OTA Trade Studies

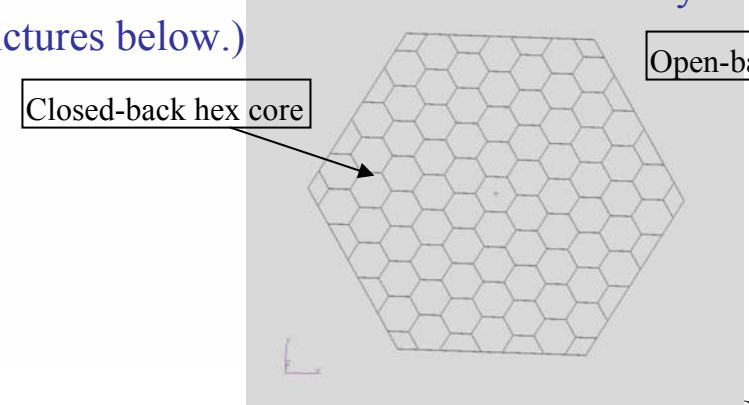
- Weight Optimization of PM, AMS and SMA. (Started PM optimization, see table below.)

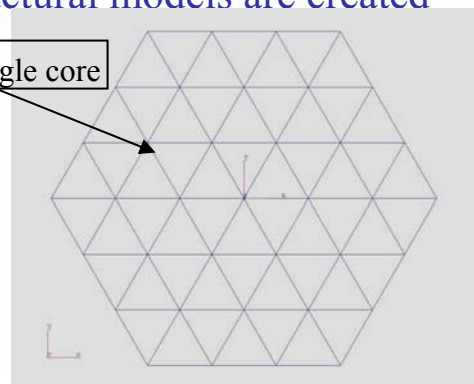
Configuration	Weight (kg) (Baseline weight is 1065.94 kg)	Fundamental Frequency (Hz)*	1 G Z Deformation (mm)
Baseline: FS = BS = 7.3 mm	-	30.19	.289
FS = 7.3 mm, BS =5.0 mm	-112.56	29.77	.298
FS = 7.3 mm, BS = 3.0 mm	-210.44	28.49	.330
FS = BS = 5.0 mm	-225.12	29.35	.309

*For optimization study, model is only PM without mounts. PM is held at mount locations in all six degrees of freedom.

- Sensitivity to PM mount design, location, and stiffness
- PM Quilting Effects (PM deformation due to thermal loads)
- Stiffness analysis of SM tower due to stiffness of hinges/latches

- PM open-back versus closed-back structural/thermal analysis. (Structural models are created for this study, see pictures below.)





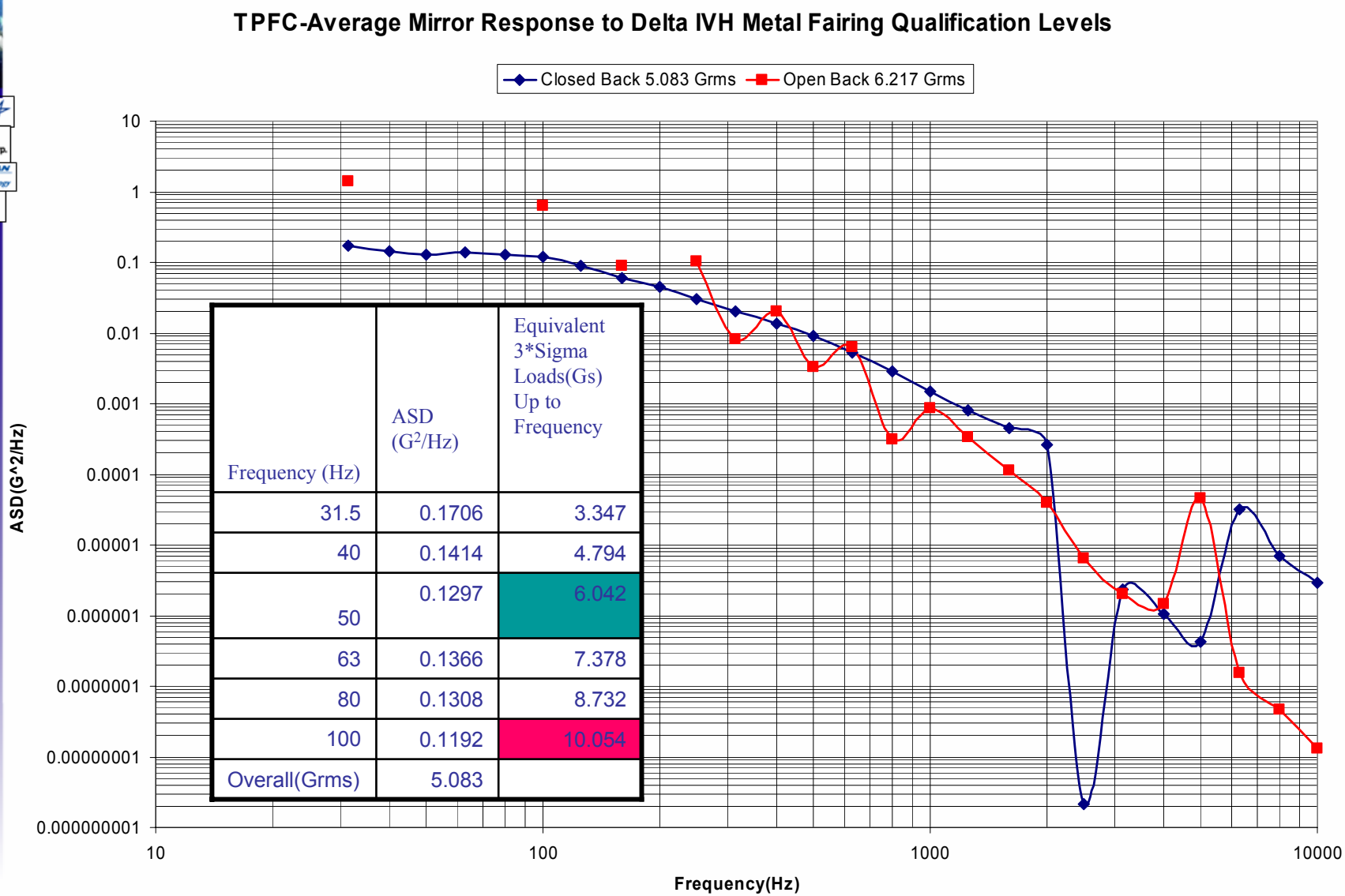
Conclusion

- PM and mount flight baseline 1 design was analyzed and found acceptable for stiffness and gravity sag, however, the design did not meet the launch load requirement. Only the inclusion of launch locks and additional weight were demonstrated to meet this requirement, however additional alternatives will be analyzed.
- Future studies will continue to investigate the PM launch loads issue and look into weight reduction of the PM and OTA designs.

PM Structural Analysis

Backup Slides

PM Acoustics Analysis

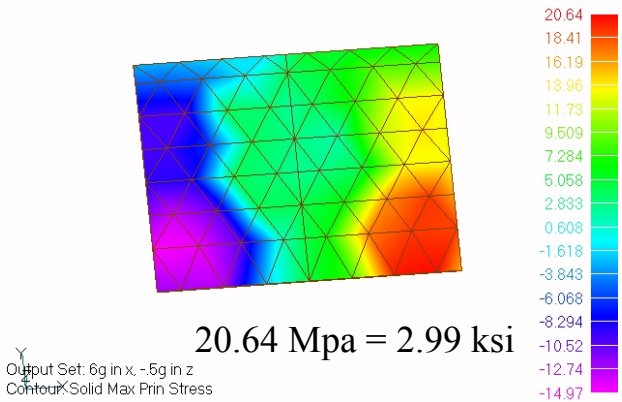


Frequency (Hz)	ASD (G^2/Hz)	Equivalent 3*Sigma Loads(Gs) Up to Frequency
31.5	0.1706	3.347
40	0.1414	4.794
50	0.1297	6.042
63	0.1366	7.378
80	0.1308	8.732
100	0.1192	10.054
Overall(Grms)	5.083	

PM Stress Analysis: Flight Baseline 1 Results

6G in X & .5G in -Z

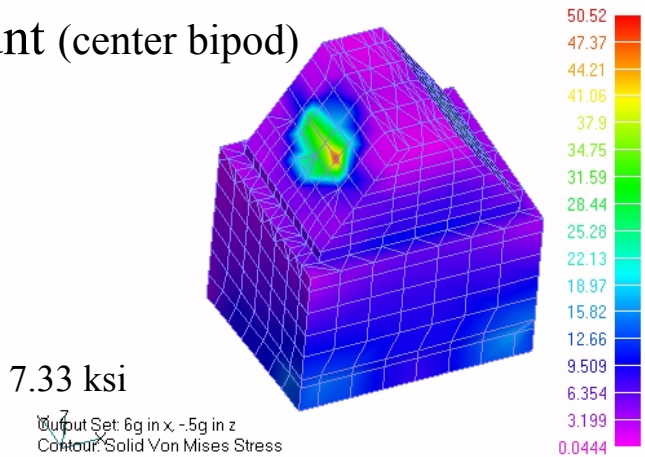
RTV (center bipod)



20.64 Mpa = 2.99 ksi

6G in X & .5G in -Z

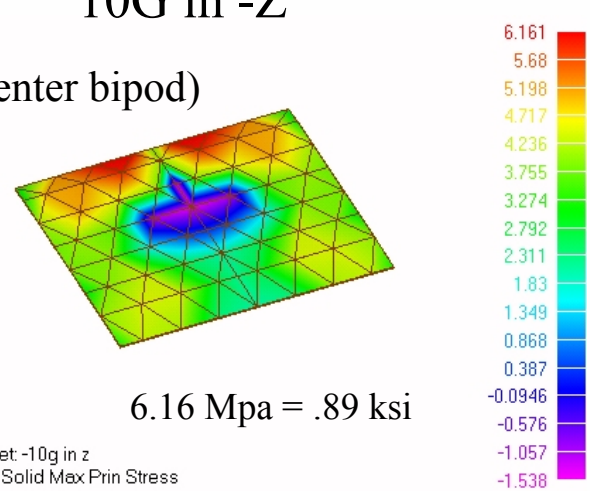
Invar Mount (center bipod)



50.52 Mpa = 7.33 ksi

10G in -Z

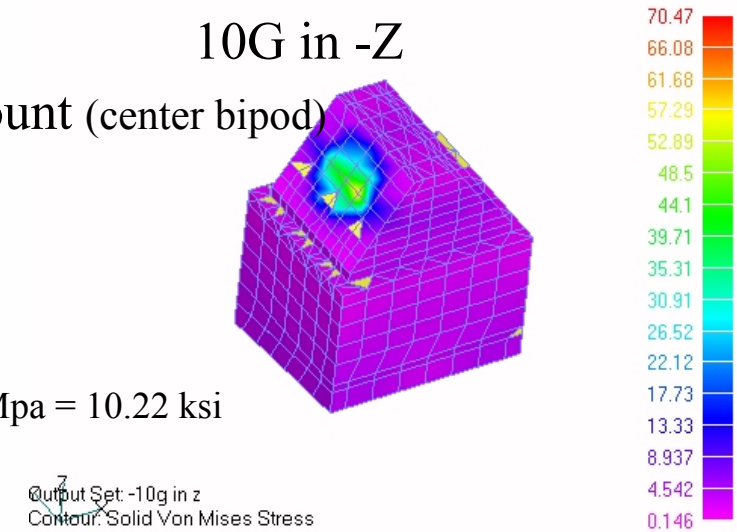
RTV (center bipod)



6.16 Mpa = .89 ksi

10G in -Z

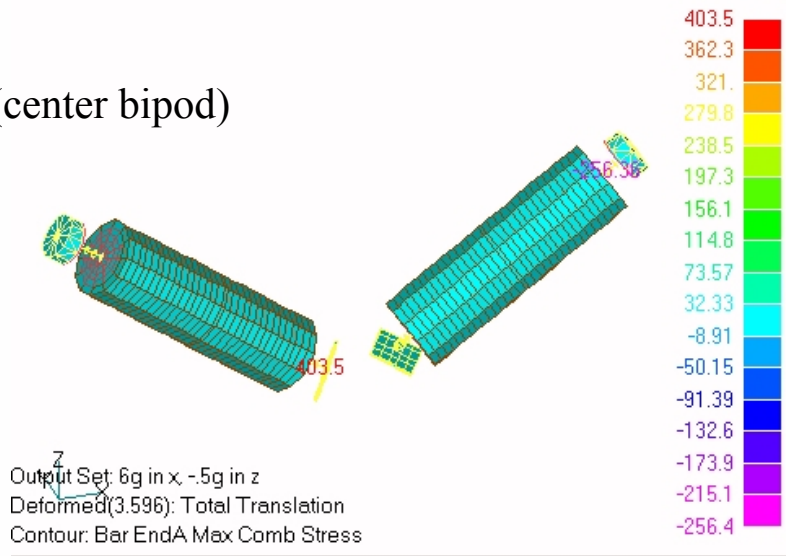
Invar Mount (center bipod)



70.47 Mpa = 10.22 ksi

PM Stress Analysis: Flight Baseline 1 Results

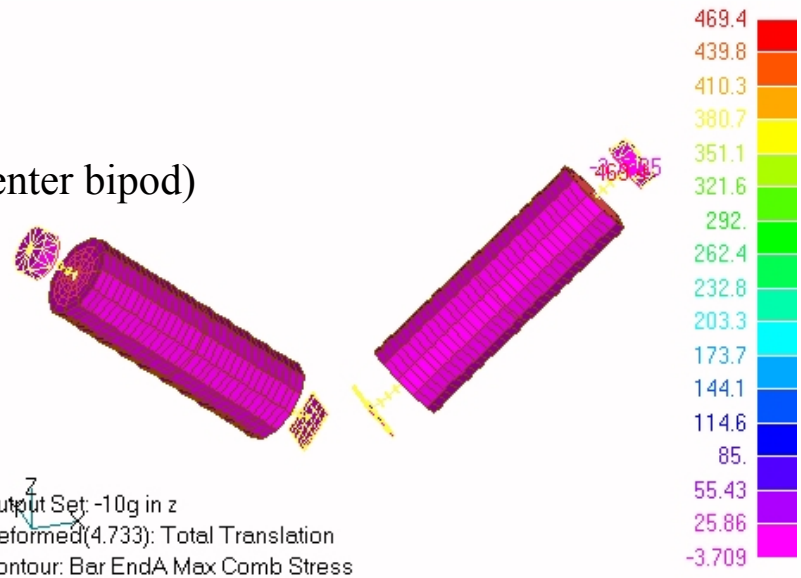
Ti Bar (center bipod)



6G in X & .5G in -Z

403.5 Mpa = 58.5 ksi

Ti Bar (center bipod)



10G in -Z

469.4 Mpa = 68.08 ksi

Lockheed Martin
Ball Aerospace & Technologies Corp.
Northrop Grumman Space Technology
TC Technology
nightsky systems

TPF Terrestrial Planet Finder

ACS Models, Performance Results & Future Studies

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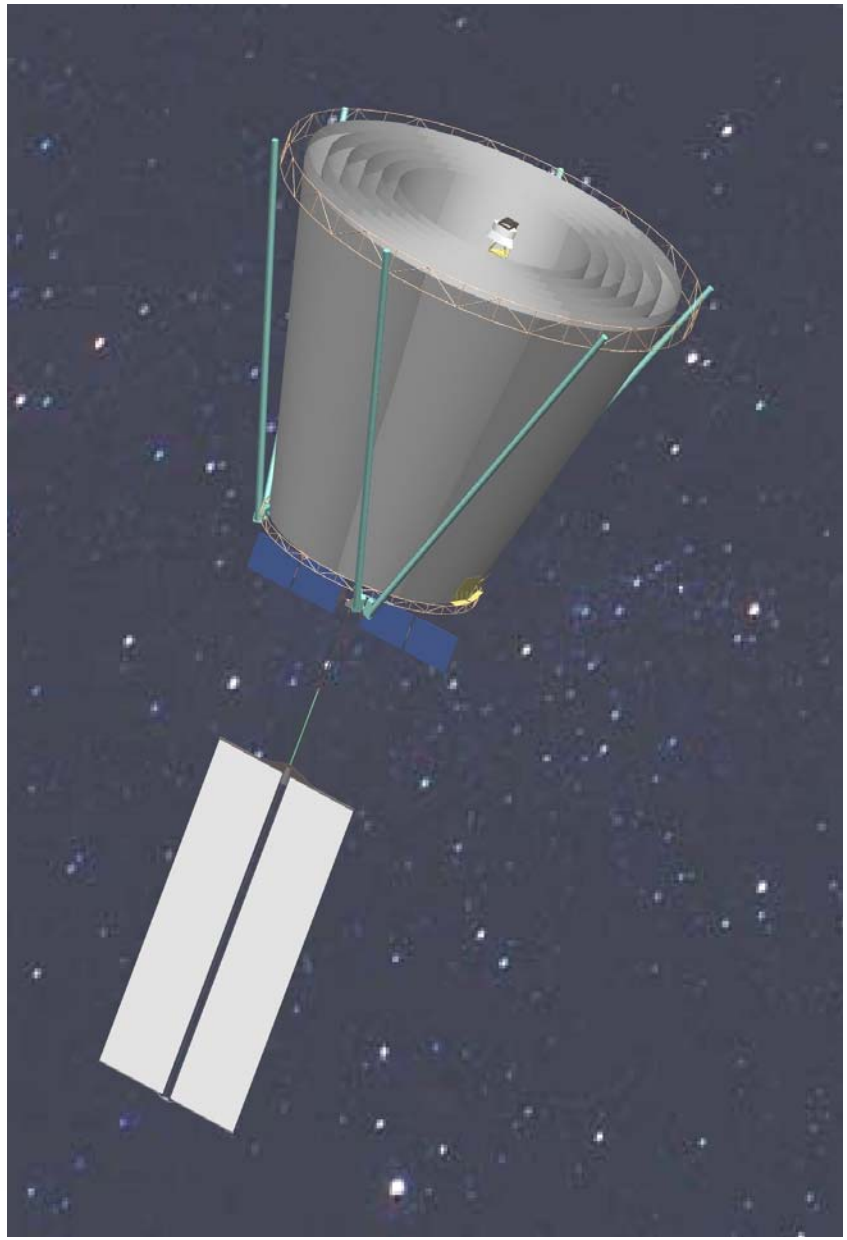
Contributors:
Larry Dewell (LMCO)
Alice Liu (GSFC)
James Alexander (JPL)

11-12 July 2005



Outline

- Objectives and methodology
- Integrated dynamics model
  - Structure
  - Optics
  - Disturbance sources
  - Uncertainty modeling
  - Control/isolation point design
    - Passive
    - Active
- Nominal performance
- Sensitivity results
- Slew/settle performance for 30 degree dither

Objectives

- Analyze jitter performance
  - RMS motions of optical elements, and of mirror deformation
  - Assess performance relative to error budget
  - Support system design iteration
    - Identify critical structural design parameters
    - Performance assessment of design trades
      - Reaction wheel placement, sensor location, et cetera
- Hand off jitter predictions to JPL for contrast simulation
  - Validate error budget
- Analyze transient performance
  - Slew/settle time
- Define control system requirements
  - Architecture
  - Loop shape
  - Sensor/actuator requirements: stroke, resolution, bandwidth

Integrated dynamics model

- Fully coupled dynamic model from disturbance inputs to optical performance
  - Disturbance models to represent physical disturbances
    - Reaction wheel imbalance
    - Sensor noise
    - Actuator noise
  - Structural model of observatory dynamics
  - Active control systems
  - Optical models map physical motions to optical response
- Two integrated models are used
  - High order linear model for analysis of high-bandwidth disturbances
    - 1000-2000 modes
    - Disturbance-Optics-Controls-Structures (DOCS) Toolbox in MATLAB
  - Low order nonlinear model for transient response simulation
    - 35 modes, Simulink®
  - Cross validation of predictions
    - Common design vector

Structure

- Structural models provided by JPL in the form of a Normal Modes model
  - Andy Kissil (Sandra Irish et. al. at GSFC provide the telescope model)
  - 3 structural models are used
    - Passive isolation (between payload and Support Module)
    - Active isolation with reaction wheel assembly isolator (payload and Support Module are completely separate)
    - Active isolation with hard mounted RWA
- Modal damping vector defined using Strain Energy Fractions
  - Best damping estimate with knockdown

$$\zeta_i = \sum_j F_{ij}\zeta_j$$

- Converted to state space model using input/output node definitions
  - Projection equations used to decompose optical node motions consistent with the error budget
    - Deformation of the primary: tip/tilt removed
    - Structural deformation: rigid motion of the optics relative to the primary
    - Rigid Body Pointing: all 21 optics moving "rigidly", ie no relative motion
- Full order models have ~7200 modes 0-300Hz
- Three reduced order models are used
  - Medium: ~2000 modes, used for analysis
  - Small: ~1000 modes, used for design
  - Slew: ~30 dominant LOS modes 0-10Hz

Component damping

Component	Best estimate	Knock down	Nominal value
Payload isolator	5%	2	2.5%
RWA isolator	5%	1.2	4.17%
Sunshield	1%	3	0.33%
Bus	0.5%	5	0.1%
OTA	0.5%	5	0.1%

Optics

- Optical models are provided in the form of linear sensitivity matrices that map structural node motions to optical response (JPL/Phillip Dumont)
  - Centroid on mask (LOS)
  - Beam walk on all 21 optics
    - Post processed to enforce zero beam walk on the DM
      - Beam walk is defined by the chief ray, which by definition has zero beam walk on the DM
  - Structural deformation aberrations
    - WFE at the mask due to rigid optics motions
  - Optical deformation aberrations
    - WFE at the mask due to deformation of the primary
      - The SM, M3, and M4 are meshed but were considered rigid for this cycle

Disturbance sources: RW

- The baseline design uses 6 Goodrich E wheels in a pyramid
- The reaction wheels are modeled as a sum of sinusoidal disturbances acting at harmonics of the wheelspeed

$$d(t) = \sum_{i=1}^{N_h} C_i f_{\mathrm{rw}}^2 \sin(2\pi h_i f_{\mathrm{rw}} t + \phi_i)$$

- Disturbance coefficients are derived from curve fits to force/torque vs RPM data
- Disturbance fundamental corresponds to static/dynamic imbalance
  - 0.273 g-cm, 21.4 g-cm^2
  - Easily achievable with Fine Balancing option
- The structural/optical response is computed by RSS'ing the responses from each force/moment component from each wheel

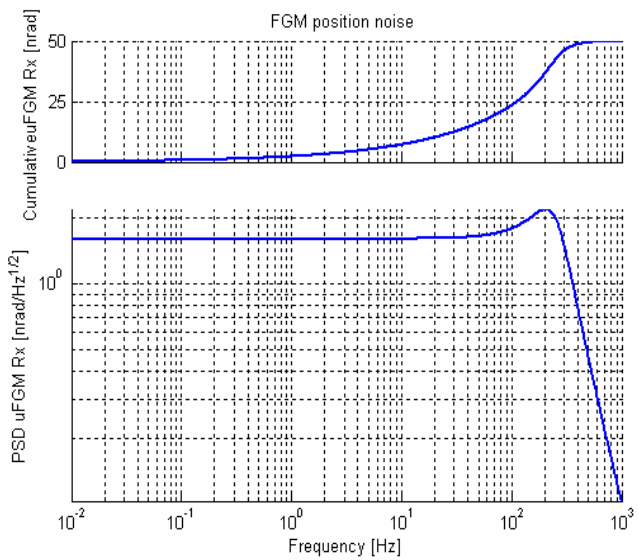
$$d(j\omega_i) = C_i f_{\mathrm{rw}}^2 \delta(j\omega_i) e^{j\phi_i}$$

$$z(\Omega) = \sqrt{\frac{1}{\sqrt{2}} \sum_{i=1}^{N_h} |G_{zd}(j\omega_i)|^2 |d(j\omega_i)|^2}$$

- The response is scaled to approximate 2 of the 6 wheels spinning at the same speed
- Maximum wheelspeed is 3850 RPM (64 RPS)
  - Minimum wheelspeed 3RPS if jitter performance requires it

Disturbance sources: noises

- All sensors have associated noise
  - Noise is modeled as sampled white noise
    - Parameters are RMS noise level and sample rate
    - See PCS Design Presentation for noise specs
  - Single pole shaping filters are used to generate the noise model from a white noise input
- All actuators have associated noise
  - SM and FGM are modeled with PZT actuators
    - Electronic noise from the power amplifiers produces position noise with a bandwidth determined by the SMA/FGM resonance
    - Position noise directly affects the optical response, and creates reaction force on the structure
  - Force actuators have a force noise spectrum
    - RMS and bandwidth
    - See PCS Design Presentation for noise specs



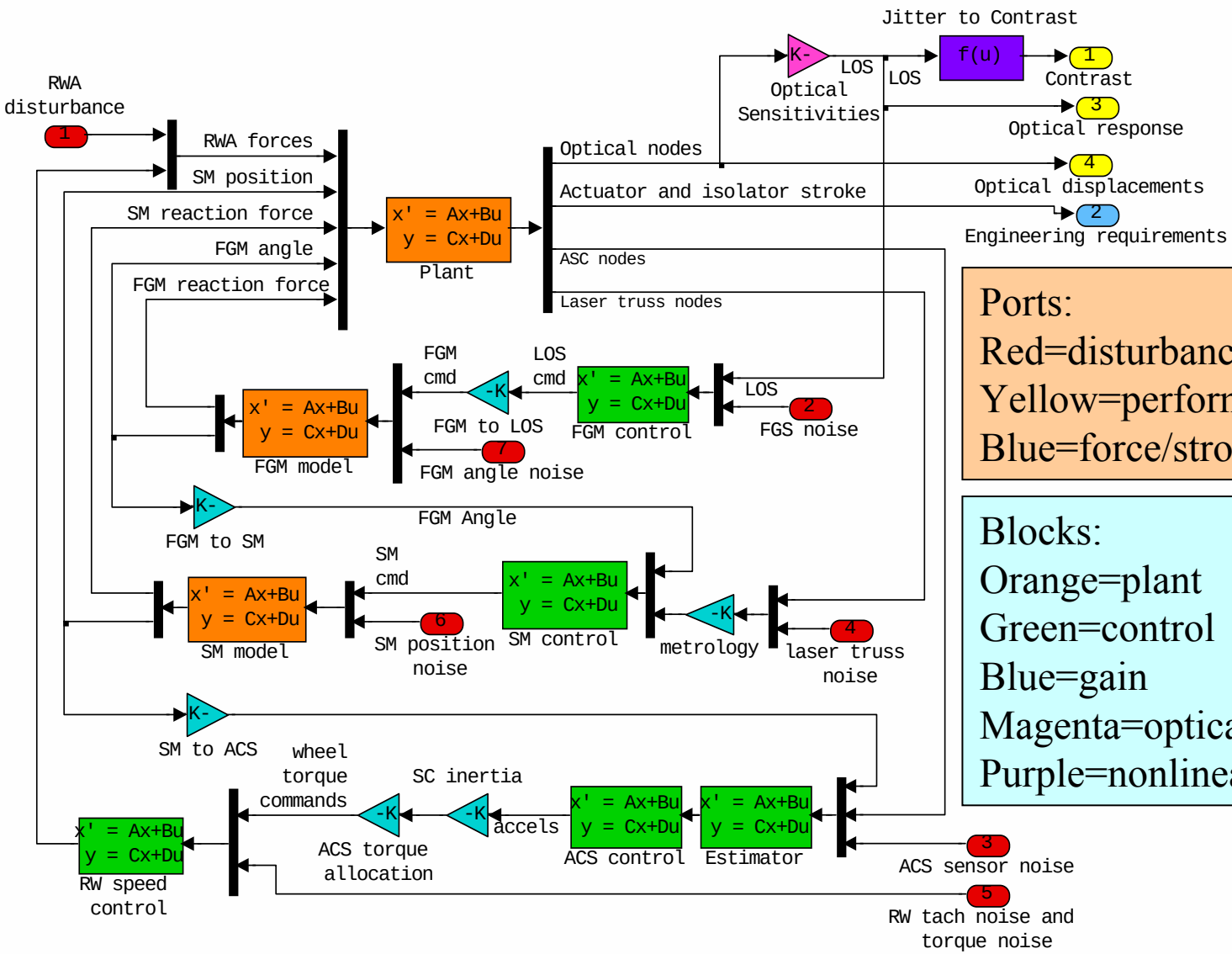
FGM position noise PSD

Uncertainty modeling

- The performance predictions include a Model Uncertainty Factor (MUF) that applies a frequency dependent gain to the response prediction
  - Approach developed by Bob O'Donnell (Veridian), Tupper Hyde (GSFC), and SIM JPL
- The MUF is developed on a component basis then assembled together
  - Defined as a dB gain then RSS'ed
- Component MUFs are functions of
  - Frequency
    - Low frequency response is usually predicted more accurately than high frequency
    - The TPFC MUF is constant 0-20Hz, increases linearly to 40Hz, then is constant to infinity
  - Model maturity
    - Component MUFs are higher for models that have no test heritage, and decrease for models that have component, subsystem, and system level testing

	Modal Gain MUF (gain …uses dB info for calcs)																	
	Below Break									Above Break								
Component	Net	Analysis Only		Component Test		Subsystem Test		Element / Observatory Test		Net	Analysis Only		Component Test		Subsystem Test		Element / Observatory Test	
RWA Disturbance	1.413	1.9953	0	1.4125	1	1.0593	0	1.0351		1.585	1.9953	0	1.5849	1	1.3725	0	1.05	
RWA Isolators	1.259	1.2589	1	1.122		1.0593		1.0351		1.585	1.5849	1	1.5849	0	1.3725	0	1.05	
Bus	1.995	1.9953	1	1.122		1.0593		1.0351		3.981	3.9811	1	1.5849	0	1.3725	0	1.05	
AMS Isolator	1.259	1.2589	1	1.122		1.0593		1.0351		1.585	1.5849	1	1.5849	0	1.3725	0	1.05	
Instrument	1.995	1.9953	1	1.122		1.0593		1.0351		3.981	3.9811	1	1.5849	0	1.3725	0	1.05	
Optical Performance	1.122	1.122	1	1.0593		1.0351		1.0233		1.122	1.122	1	1.0593	0	1.0351	0	1.05	
Product of MUF	2.98	3.47		1.52		1.14		1.08		8.28	8.80		2.80		2.03		1.29	

Passive: image control system



Ports:
Red=disturbance
Yellow=performance
Blue=force/stroke

Blocks:
Orange=plant
Green=control
Blue=gain
Magenta=optical sensitivity
Purple=nonlinear function

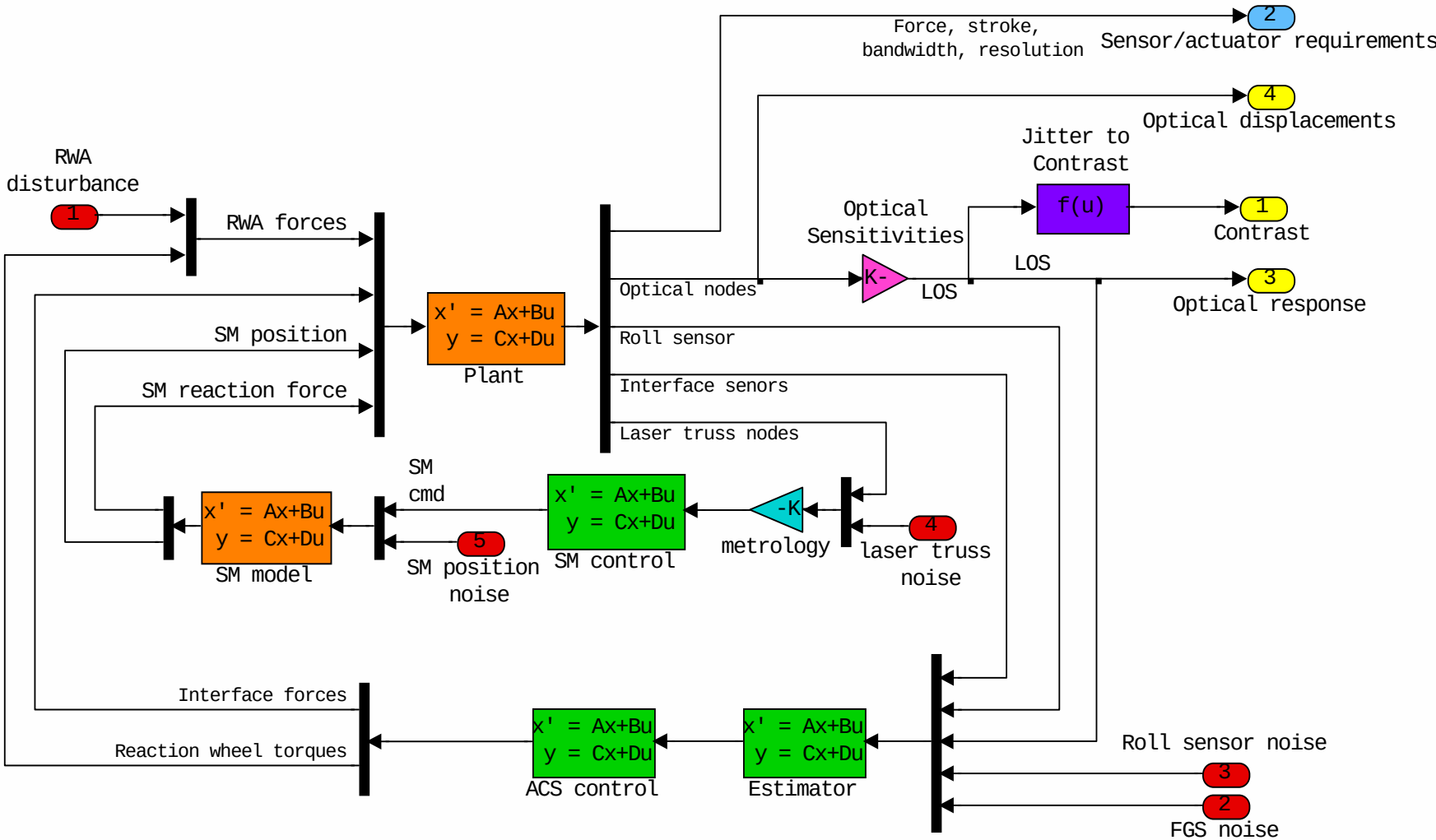
Passive system point design

- The passive design uses a two-stage passive isolator plus a three-stage image control system
  - The passive isolator consists of a 1.5Hz isolator on the Reaction Wheel Assembly, and a 1 Hz isolator between the payload and Support Module
- The image control system is designed using classical loop shaping techniques
  - Simple controllers with minimal parameters are used to enable rapid design sweeps
  - 6dB gain margin and 30 degrees phase margin are enforced for all loops
- The FGM and SM compensators are second order low pass filters with a lead network at cross over

Control loop	Parameter	Value	Sample Freq.	Margins	Bandwidth
FGM	Break freq. Lead	1 Hz 45º	500 Hz	7.01dB 25.6º	25.1 Hz
SM	Break freq. Lead	0.001 Hz 45º	100 Hz	49.11dB 45.7º	0.1 Hz
ACS	Crossover Integral T.C. ratio Estimator freq. Elliptical order Elliptical ripple Elliptical atten. Elliptical freq.	0.016Hz 0.075 10Hz 3 1dB 30dB 0.56	5Hz	9.3 dB 34.8º	0.043 Hz
RW speed control	Bandwidth Lead	1Hz 60º	100 Hz		1 Hz

- The ACS uses an inertia compensated PID design adapted from the NGST Yardstick design
- Reaction wheel speed control
  - Spin axis disturbances can be controlled with feedback from a tachometer
    - Torque noise, drag torque
  - Tachometer noise introduces additional error
  - Integral compensator with 1Hz bandwidth is used for the point design

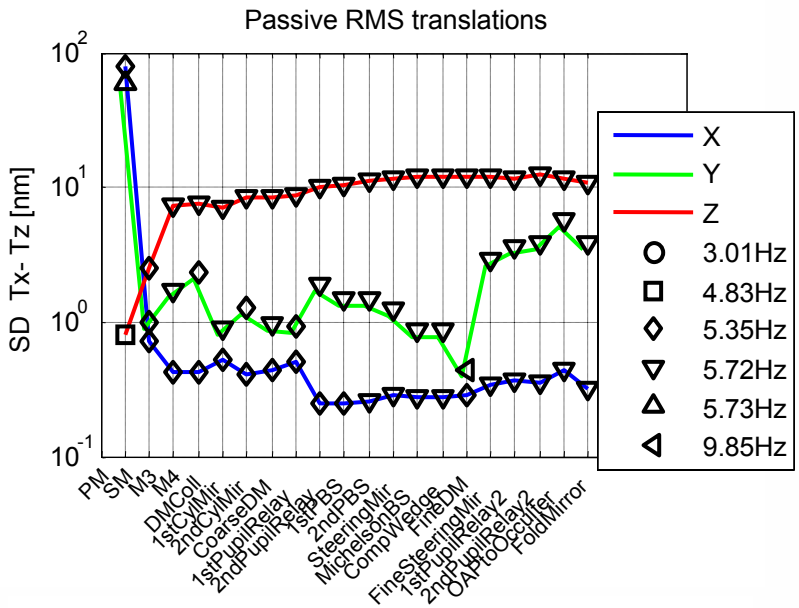
Active system loop diagram

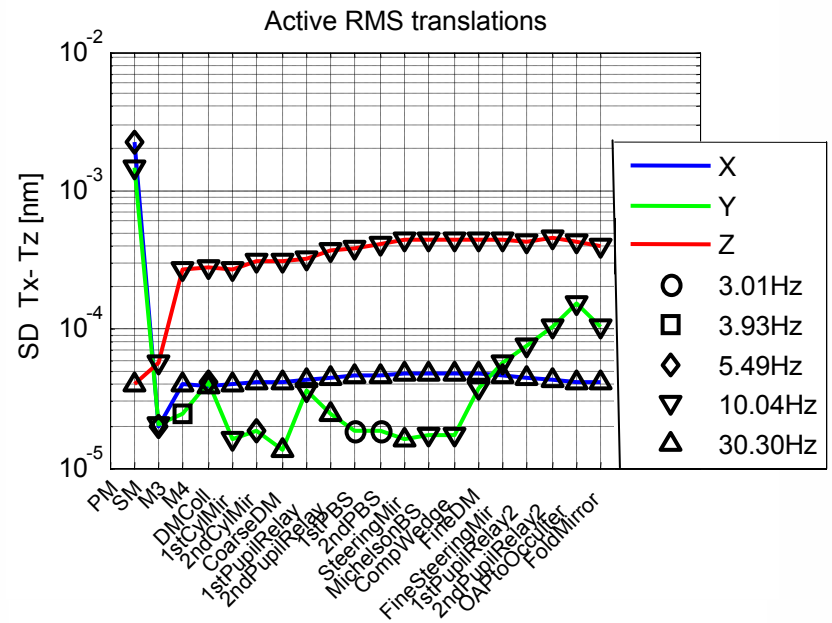


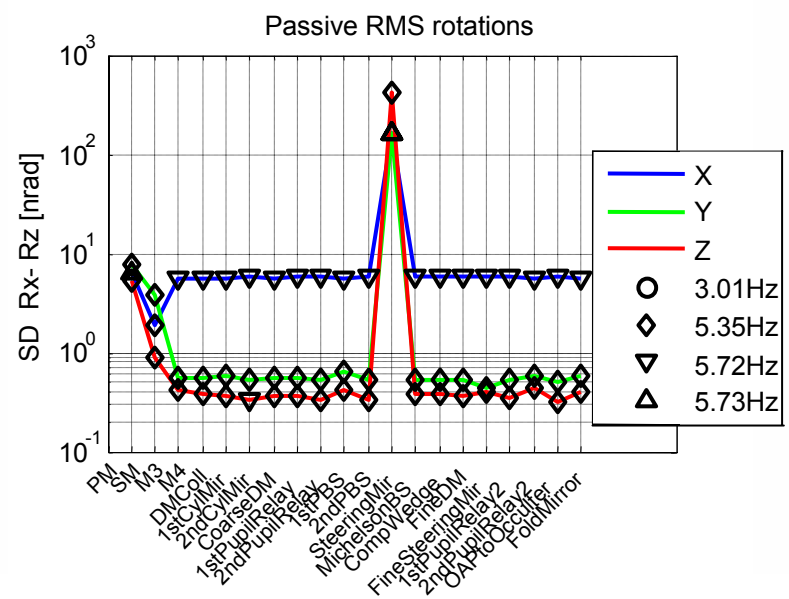
Active system point design

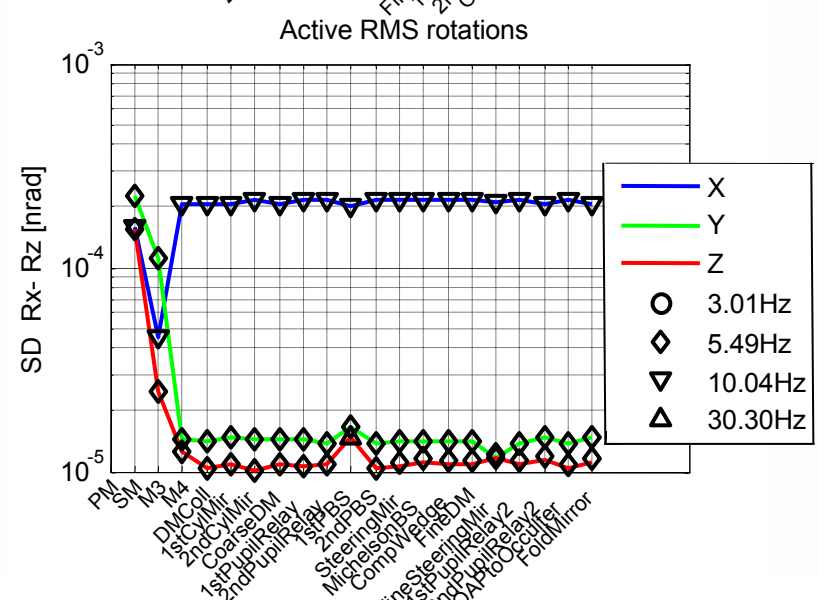
- Non-contact active isolation and pointing
  - Non-contact actuators (NCAs) impart relative force between payload and support module (0.5Hz bandwidth) to control payload inertial attitude
    - Fine Guidance Sensor for pitch/yaw
    - Payload Star Acquisition Camera for roll
    - Interface relative translation
  - Reaction wheels control payload/support module relative angle to maintain requisite interface stroke and gap
  - Pointing is only a function of quiet side (payload) sensors
    - Insensitive to support module disturbances and dynamics
- Interface is shorted by
  - Power/data cabling
    - Adds a stiffness
    - 100 N/m, 100 N-m/rad is used for the nominal results
    - 10x higher than best estimate
  - Back-EMF of the NCAs
    - Rate dependent relative force

Point design performance: physical response

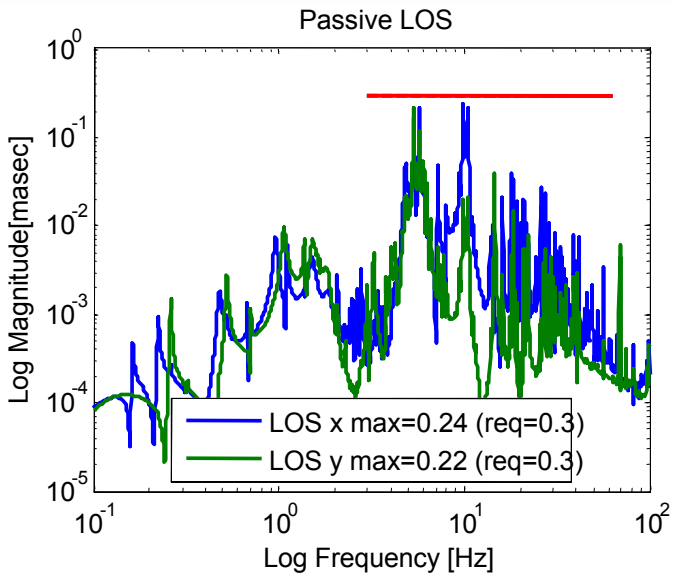




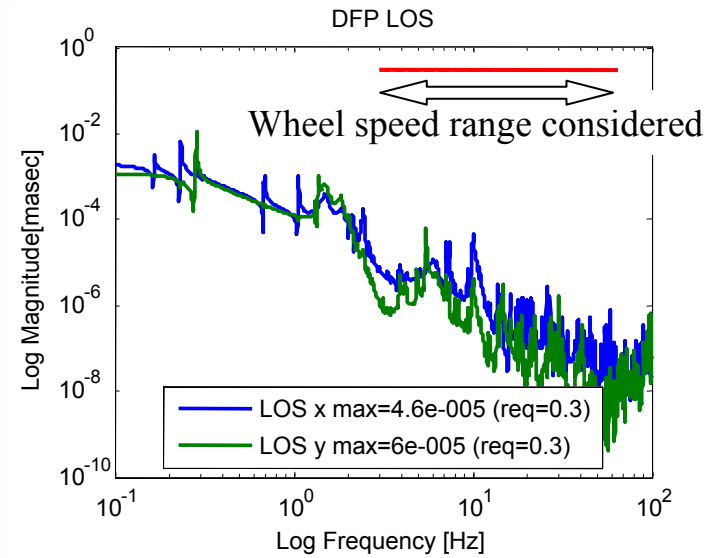


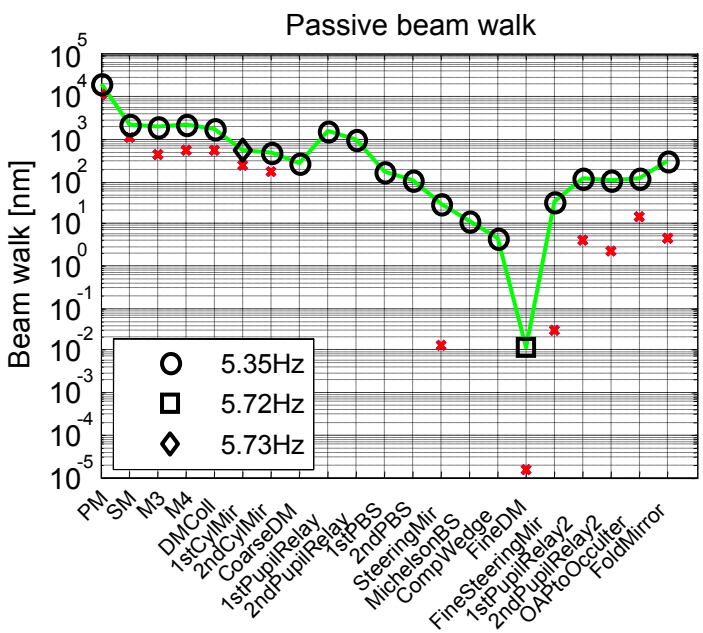


Point design performance: optical response

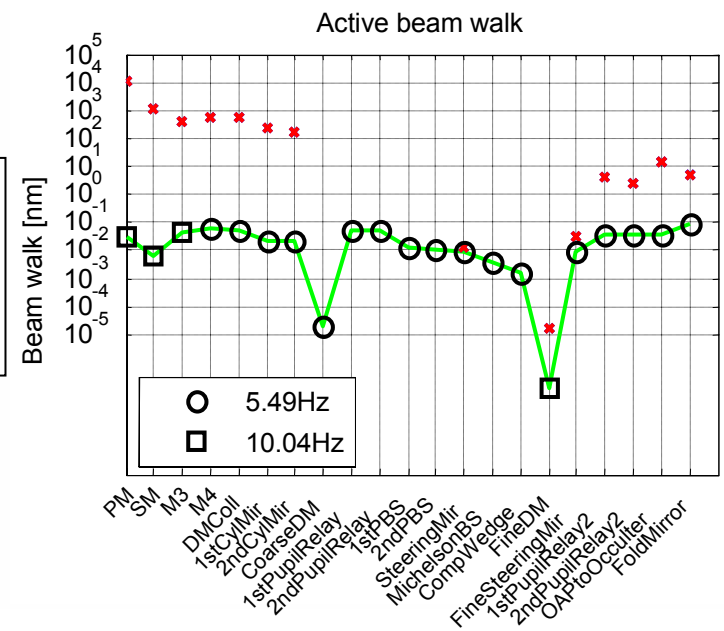


LOS Jitter Requirement

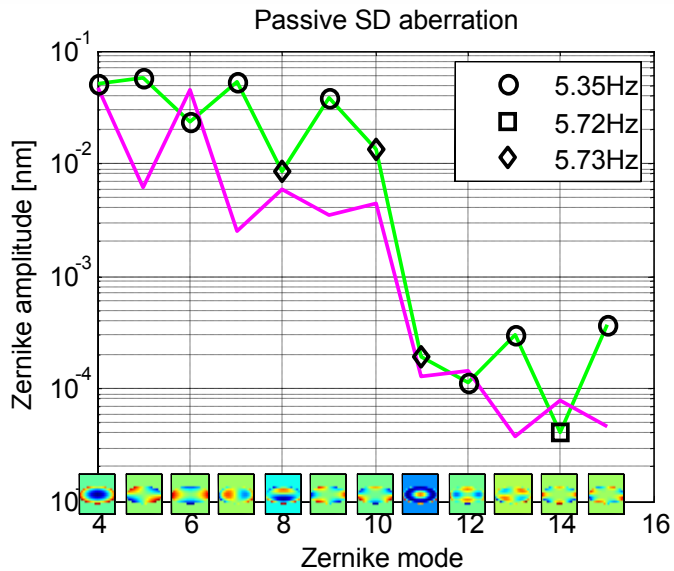




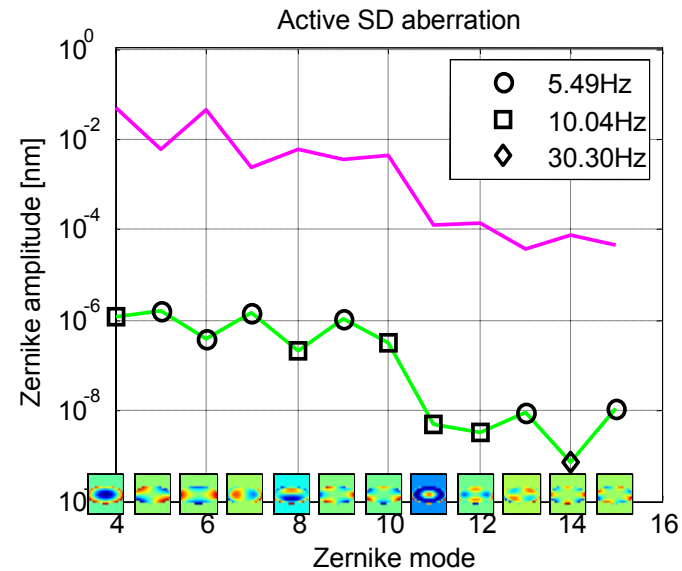
x - amount of beam walk identified in error budget

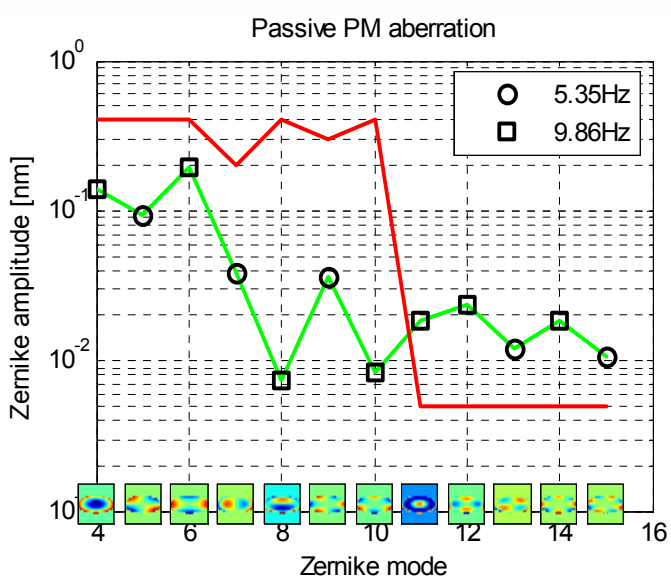


Point design performance: optical response 2

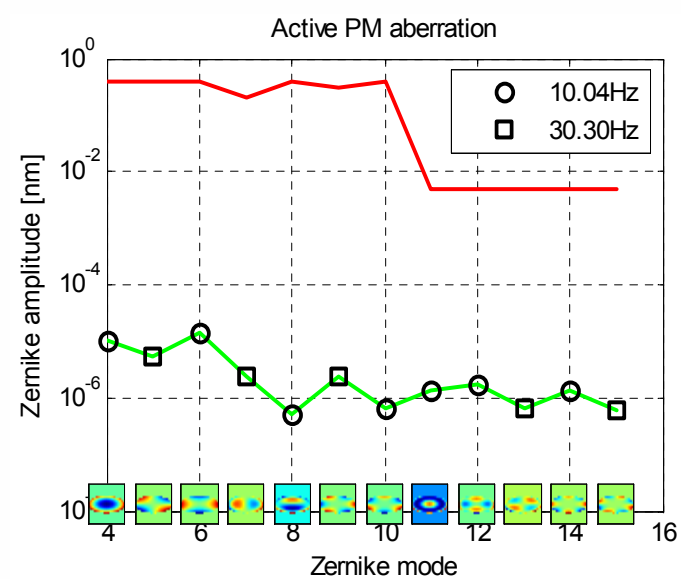


SD aberration results from physical motion requirements



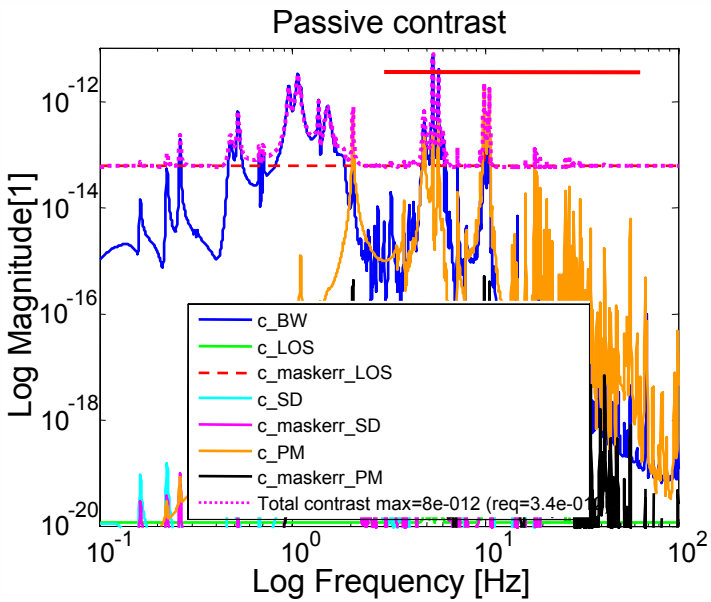


PM aberration Requirements

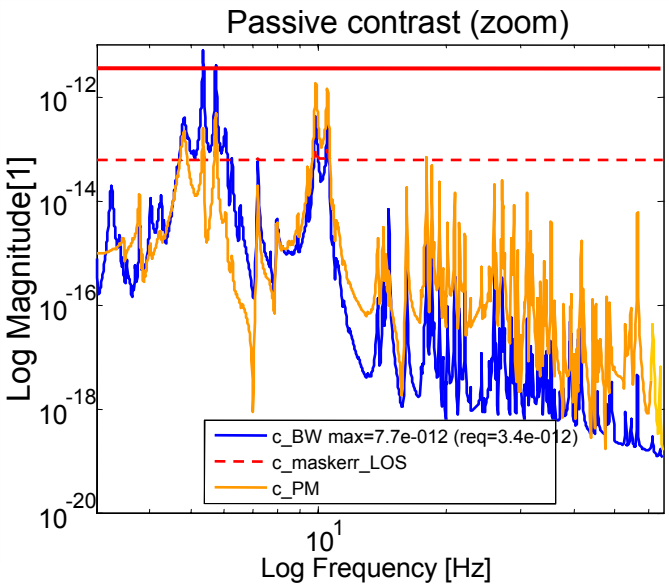


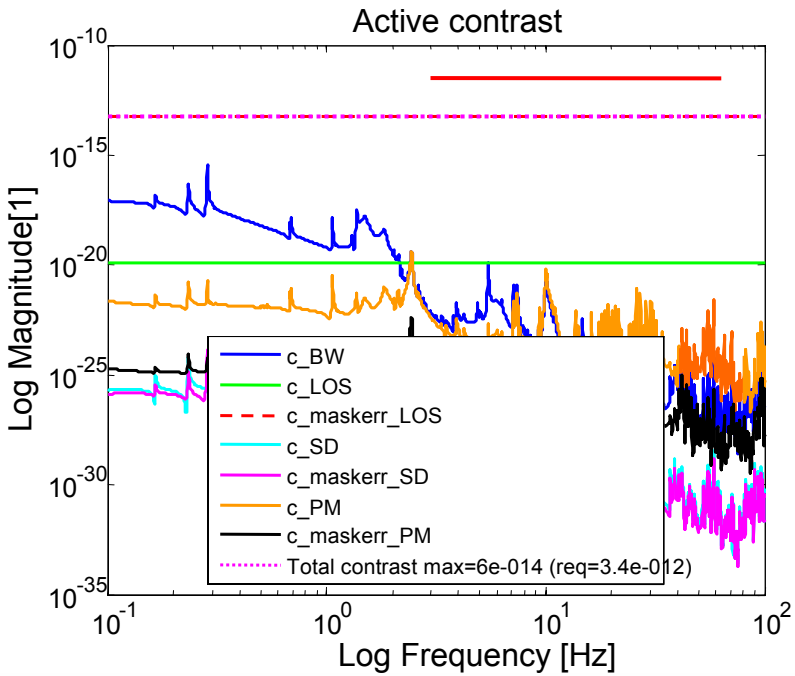
Point design performance: contrast

LOCKHEED MARTIN
Ball Aerospace & Technologies Corp.
NORTHROP GRUMMAN Space Technology
TC Technology
nightsky systems



Total Contrast Requirement





TPF Terrestrial Planet Finder

Sensitivities: contrast vs. damping

	Passive 0.1%	Passive 0.5%	Active 0.1%	Active 0.5%	Contrast Req
Beam walk	7.7e-12	2.6e-12	1.2e-20	1.1e-22	1.9e-12
LOS	8.1e-17	5.7e-18	1.2e-20	1.2e-20	9e-14
LOS mask error	9.7e-14	7.4e-14	6e-14	6e-14	5.5e-13
Structural deformation	1.6e-16	3.4e-17	3.3e-26	1.8e-27	2.8e-17
SD mask error	7.9e-17	2.7e-17	5.3e-26	6e-28	1.7e-17
PM deformation	1.8e-12	6.6e-13	5.9e-21	8.9e-21	8.5e-13
PM deform. mask error	4.9e-16	1.8e-16	2.6e-24	1.3e-23	5.2e-15
Total contrast	9.5e-12	3.3e-12	6e-14	6e-14	3.4e-12

Passive: sensitivities

- Reactuated FGM
  - Zero the reaction force on the payload
  - Decrease the quiet side noise
- Reactuated SM
  - Zero the reaction force on the tower
  - Decrease the quiet side noise
- 20Hz SM
  - Reactuate the SM (to decouple from the tower modes)
  - Boost the FGM bandwidth to 100Hz, SM bandwidth to 20Hz
  - Decrease the beam walk
- Tower damping
  - 2% damping on the tower modes at 5.35, 5.7, 9.8, and 10.5Hz
  - Modes 1093, 1094, 1145, 1146, 1592, 1639
  - No physical damper (just changed modal damping)

Passive sensitivities: RWA to contrast

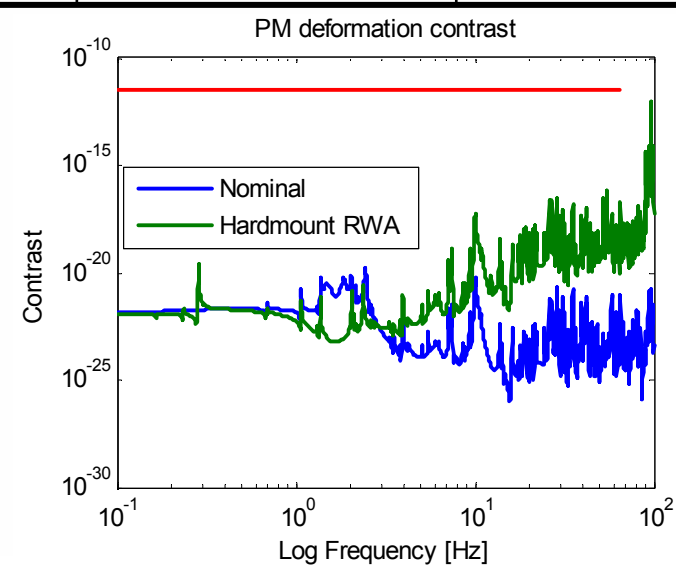
	Nominal	Reactuated FGM	Reactuated SM	Reactuated SM + 20Hz SM	2% Twr Damping	Contrast Req
Beam walk	7.8e-12	7.8e-12	8.5e-12	5e-14	3.7e-13	1.9e-12
LOS	7.7e-17	7.7e-17	1.1e-16	1.2e-20	1e-19	9e-14
LOS mask error	9.7e-14	9.7e-14	1e-13	6e-14	6.3e-14	5.5e-13
Structural deformation	1.6e-16	1.6e-16	1.9e-16	8.1e-18	3.6e-18	2.8e-17
SD mask error	8e-17	8e-17	8.7e-17	1.1e-17	2.7e-18	1.7e-17
PM deformation	1.8e-12	1.8e-12	2e-12	2e-12	2.1e-13	8.5e-13
PM deform. mask error	4.8e-16	4.8e-16	5.5e-16	5.5e-16	9.6e-17	5.2e-15
Total contrast	9.6e-12	9.6e-12	1.1e-11	2.1e-12	6.4e-13	3.4e-12

Active: sensitivities

- Increased actuator back-EMF
  - Rate dependent force at payload-support module interface
  - 10 times higher than nominal
- Hard mounted reaction wheel assembly
  - Nominal active design is significantly below the requirement
  - Remove the RWA isolator to save mass and cost
  - Hardmounted wheels would enable better packaging
    - RWA is fighting other subsystems for space at the CG

Active sensitivities: RWA to contrast

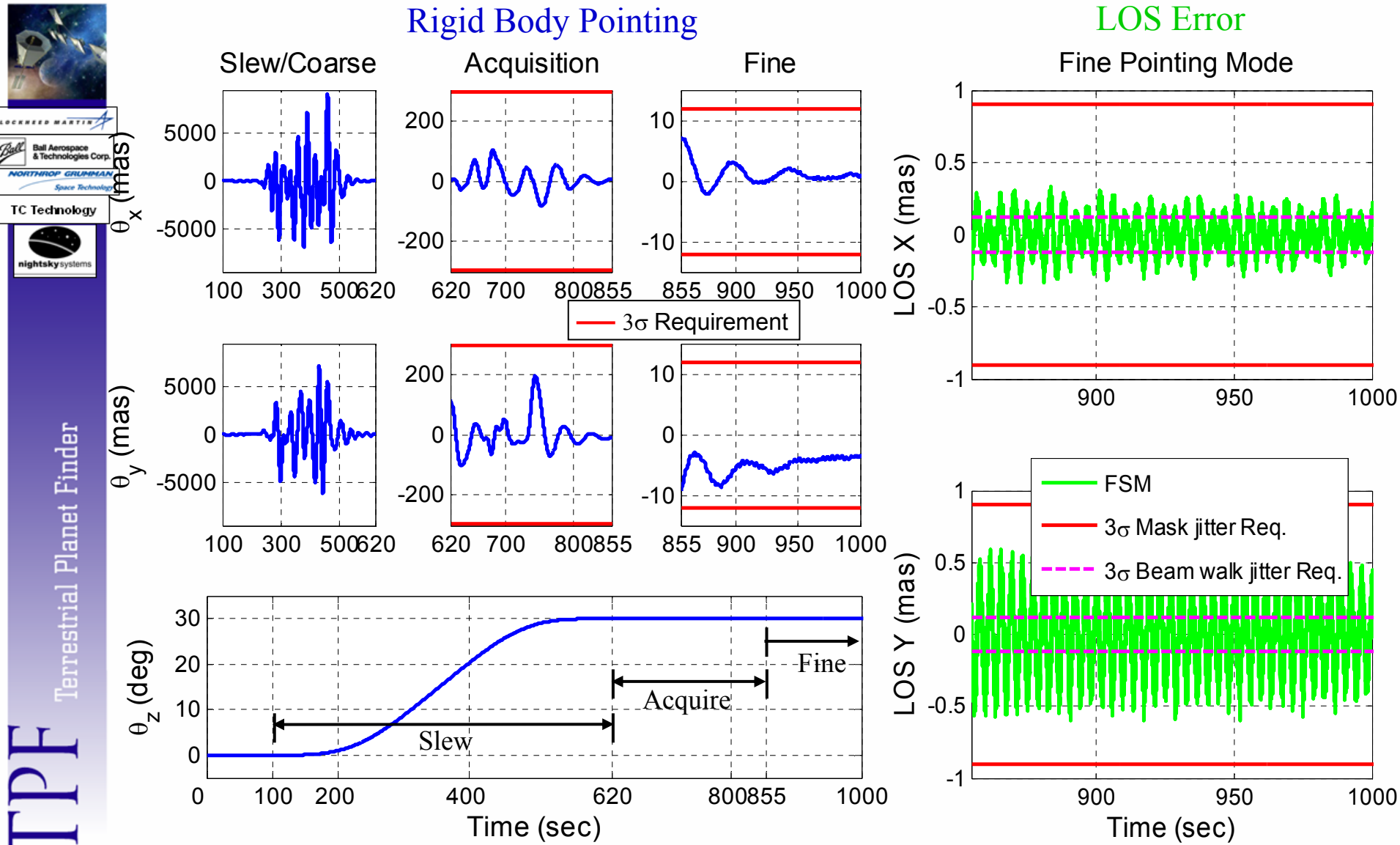
	Nominal	x10 back EMF	Hardmount RWA	Contrast Req
Beam walk	5.7e-18	5.7e-18	3.8e-16	1.9e-12
LOS	1.2e-20	1.2e-20	1.2e-20	9e-14
LOS mask error	6e-14	6e-14	6e-14	5.5e-13
Structural deformation	2.7e-24	2.7e-24	3.1e-23	2.8e-17
SD mask error	1.6e-24	1.6e-24	6.2e-24	1.7e-17
PM deformation	1.7e-20	2e-20	7.2e-17	8.5e-13
PM deform. mask error	2e-23	2.4e-23	6.3e-20	5.2e-15
Total contrast	6e-14	6e-14	6.1e-14	3.4e-12



Nonlinear Time Simulations

- Create time simulation that complements DOCS linear system analysis and incorporates nonlinearities in real system
- Perform jitter analysis due to nonlinear actuator and sensor effects (see backup slides)
  - RWA drag torque
  - RWA tachometer measurements
- Estimate slew/settle time for dithers
  - Updated 6 wheel configuration
  - Simulate acquisition sequence from coarse mode to fine observing mode

Dither (30 deg) Performance



Slew/settle time requirement (30 min = 1800 sec)

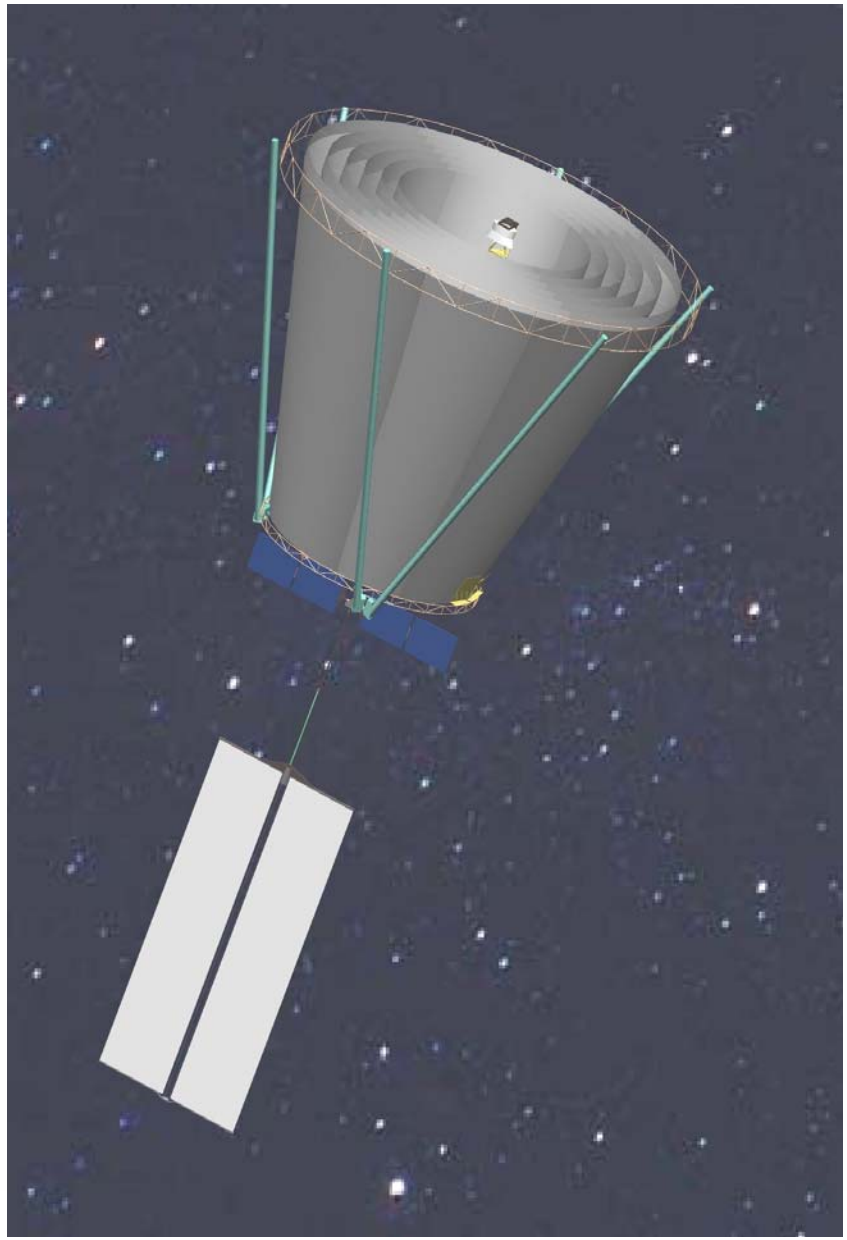
Conclusions

- Active design meets requirements with significant margin
  - May be possible to hardmount reaction wheels
- Passive design does not meet currently meet requirements
  - Several design options would improve performance
    - Passive damping
    - Reduction of reaction wheel torque noise and SM position noise
  - It meets slew/settle time requirement for rigid body pointing but does not meet beam walk jitter requirement

Future work

- Linear noise analysis
- Find a passive point design that meets requirements
  - Passive damping that provides 2% in the tower 1st and 2nd modes
    - Viscoelastic or proof mass damper
- More controller designs
- Additional mechanism disturbances
  - High gain antenna, solar array, solar sail
- Update slew simulation
  - Incorporate DFP for active isolation simulations
  - Continue to improve actuator and sensor models

Backup Slides



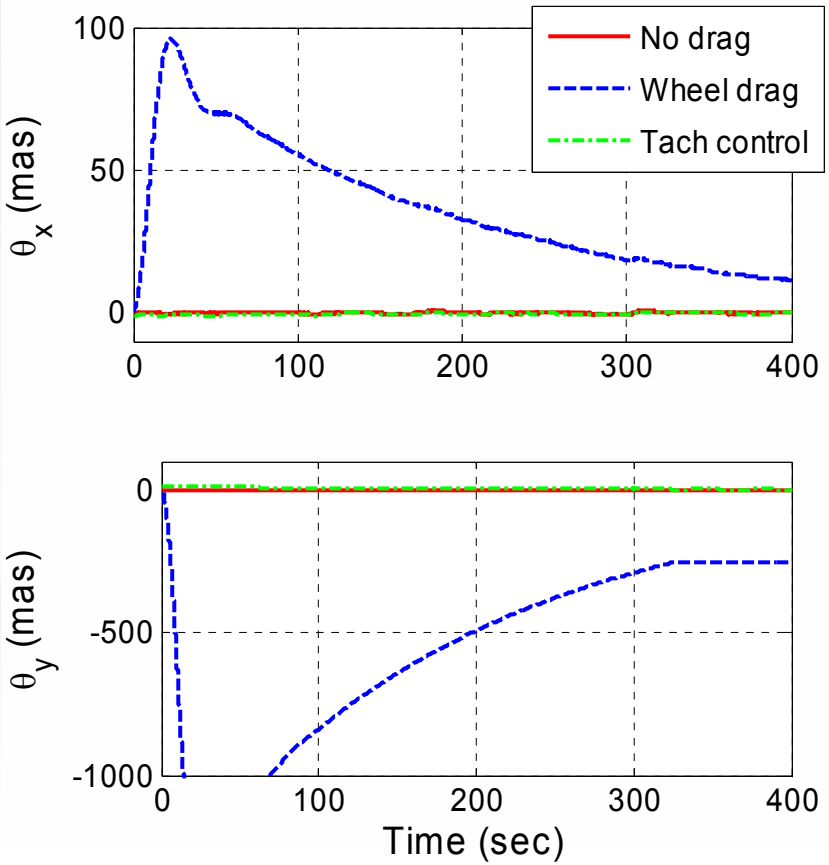
Simulation Model Descriptions

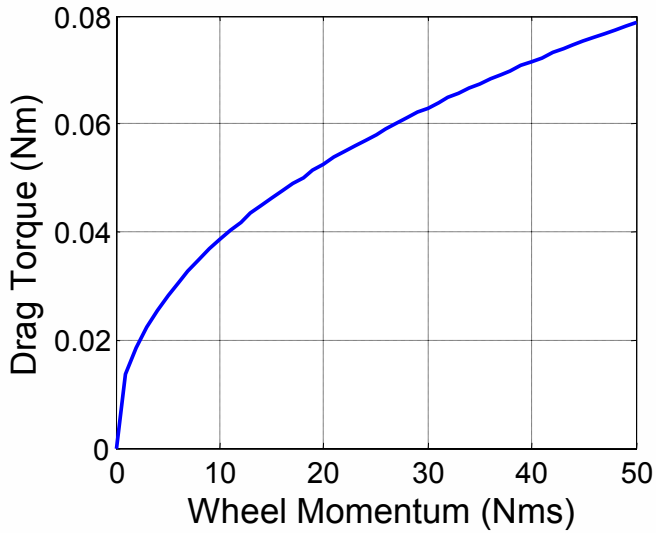
- Nonlinear time simulation is created in Simulink, modified from JWST Yardstick model
  - Captures nonlinear attitude rigid body dynamics (gyroscopic effects)
  - Include a reduced set of significant flexible modes (35 modes)
  - LOS and beam walk sensitivities are currently implemented
  - Same controller, vibration isolation, actuator, and sensor models are implemented as the DOCS linear model
- Slew control design description
  - PD controller plus acceleration feedforward
  - Structure filter used to reduce flexible mode responses and settling time
- Disturbances
  - RWA: imbalances, torque quantization, drag torque, and torque noise
  - Sensor noises: gyro, star tracker, PSAC, FGS, orientation of FGM, orientation of SM, and tachometer quantization

Wheel Drag Effects

- Drag torque
  - Model is a curve fit from vendor data (MAP, TRMM)

$$T_{\text{drag}} = \alpha \operatorname{atan}(\beta H_{\text{rw}}^{\gamma}) \qquad \alpha = 0.341 \qquad \beta = 0.0399$$

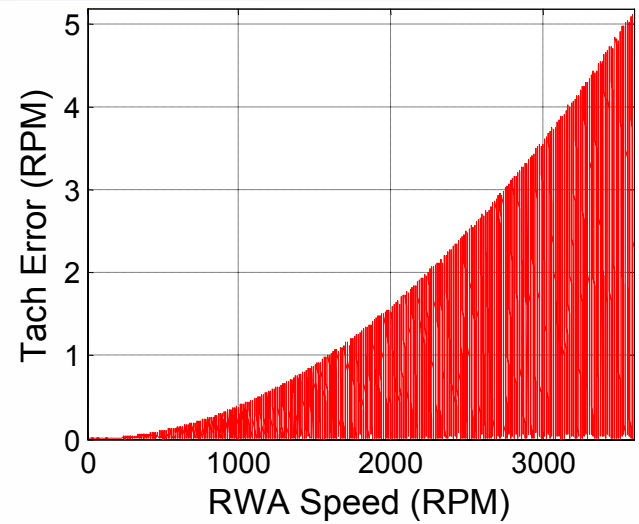


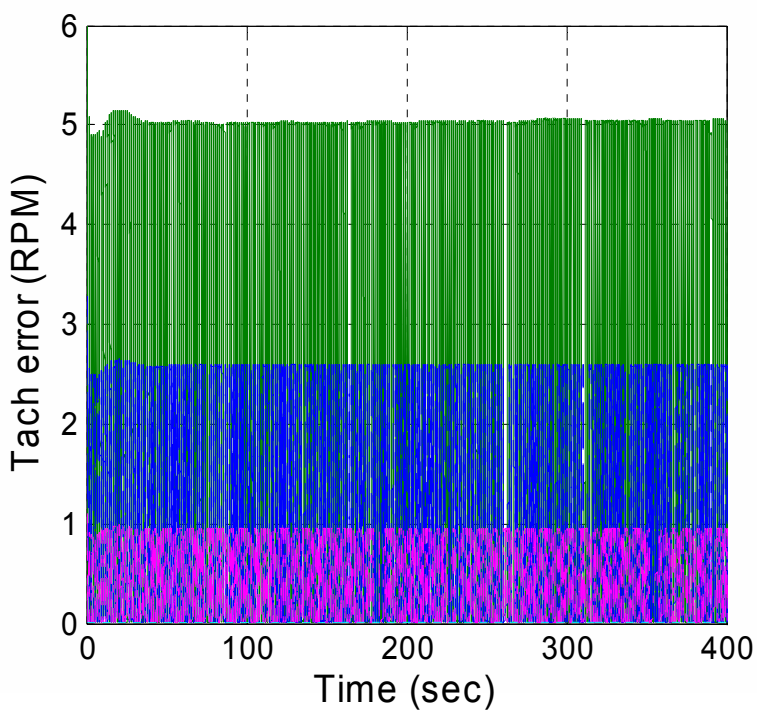


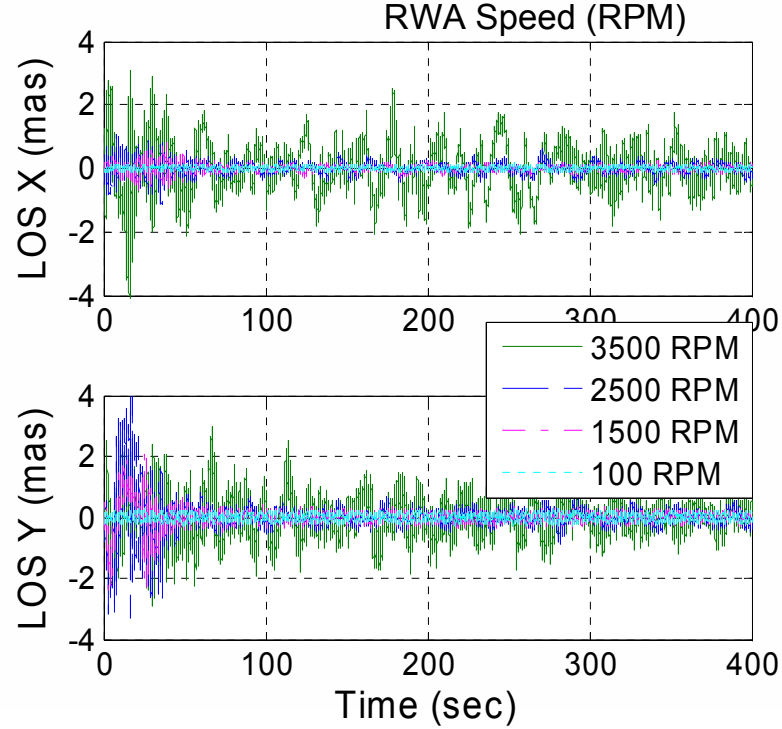
- ACS integral control cannot act fast enough to cancel changing drag torque
- Faster wheel tachometer loop is closed to compensate for drag torque

Wheel Tachometer Measurement Errors

- Tachometer readout
  - 72 pulses per revolution for Goodrich E wheels
  - Tach error increases with wheel speed due to less time elapsed between two pulses





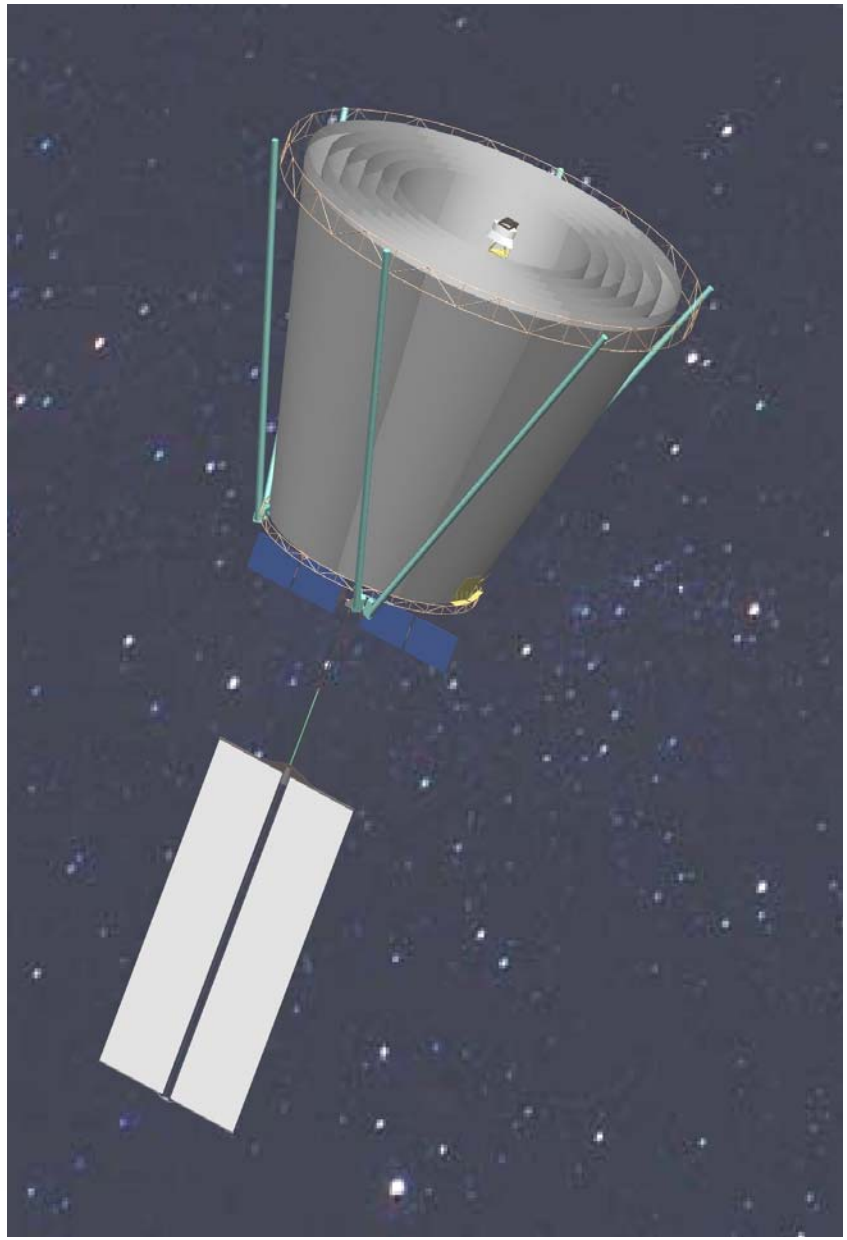


Modeling Summary

Marie Levine

Contributors:
Modeling Team

11-12 July 2005



Iterative Design/Analysis Cycle Process

Cycle "n"

Cycle "n + 1"

Design Evolution
- Alternate Concepts
- Trade Study Results

Changing Conditions
- Emerging Requirements
- Reprioritized Goals
- New Constraints

4/1/05

Design Freeze
- Systems Eng'rg
- Baseline Design
- CAD model

5/6/05

Analysis Plan
- Results Goals
- Case Priorities

10/07/05

Design Refinement Decisions
- Updated Baseline Design
- Updated Req's for Cycle n+1
- Consolidated Alternate Design(s)

5/6/05

Model Creation
- Optical
- Structural FEMs
- Thermal
- Dynamics

Integrated Analyses
- Nominal Design & Conditions

Sensitivity Analyses & Design Perturbations

7/12/05

Prelim Analysis Results
- Review
- Plan Assessment

Legend

Cycle 1 Target Dates

Start — Done

Modeling path →

TPF Terrestrial Planet Finder

Cycle 1 Alternate Concepts for Analysis

1. Pointing Control System
   - Passive vs dynamic isolation
   - RWA design option trades: size, position, number
2. PM Mirror Architecture
   - Racetrack monolithic PMA vs Elliptical
   - PM mounts & launch locks
   - Closed-back vs open-backed
   - PMA core segmentation: hex vs square
   - Actuated PMA vs coarse DM
3. OTA Design
   - Light-weighted SMA & AMS
   - OTA baffle concept
4. Sunshield Design
   - Sunshield architecture: conic vs sugar scoop
   - Active thermal design for PMA & SMA
   - Sunshield circularity sensitivity
   - Active thermal control layer in sunshield

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ACS Trade Studies

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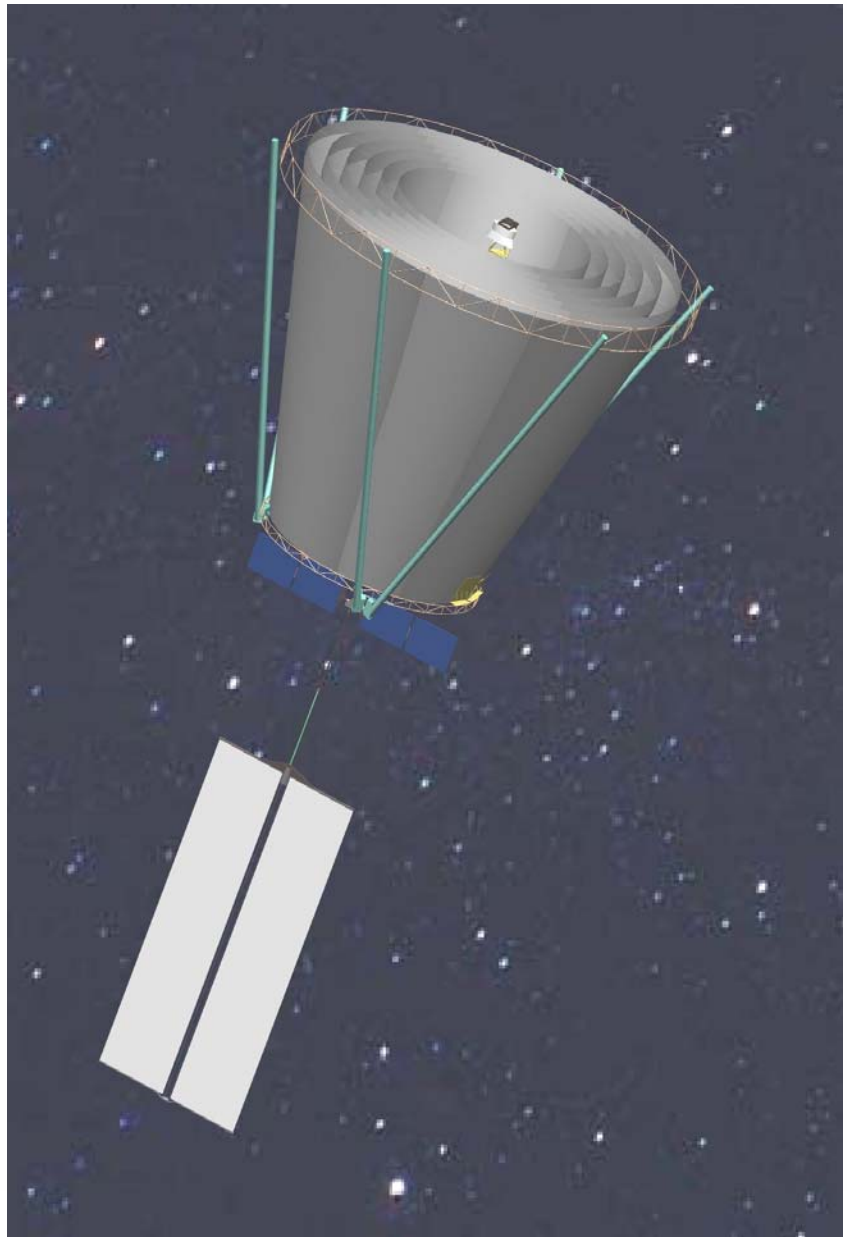

Trade Studies

- Reaction Wheels Trades
  - Reaction wheel location trade
    - Move wheels away from the CG to free up space, at the cost of potentially amplifying induced jitter
  - Size
    - Momentum buildup – (solar pressure, etc)
    - Time duration between momentum dumps
    - Torque Capabilities needed to complete slews with time period
    - Isolation Stage on reaction wheels versus wheel height
    - Use more, smaller wheels
- Fine Guidance Sensor (FGS) design
  - Location of focal plane and implementation (exact pickoff location)
  - FSM design (bandwidth, range of motion,)
  - FGS sensor model

Trade Studies

- Location of Payload Acquisition Camera Trade
  - Location (Currently looking through the baffle)
  - View of sky
  - Dynamic stability
- Active isolation
  - Roll sensor trade (from payload or support module)
  - Advantage of eliminating SM control system and possibly FGM control loop
- Solar Sail disturbance on S/C
- Map disturbances to contrast budget (provided preliminary results)
  - provides method directly looking at disturbance influences

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Racetrack configurations for the TPFC Primary Mirror

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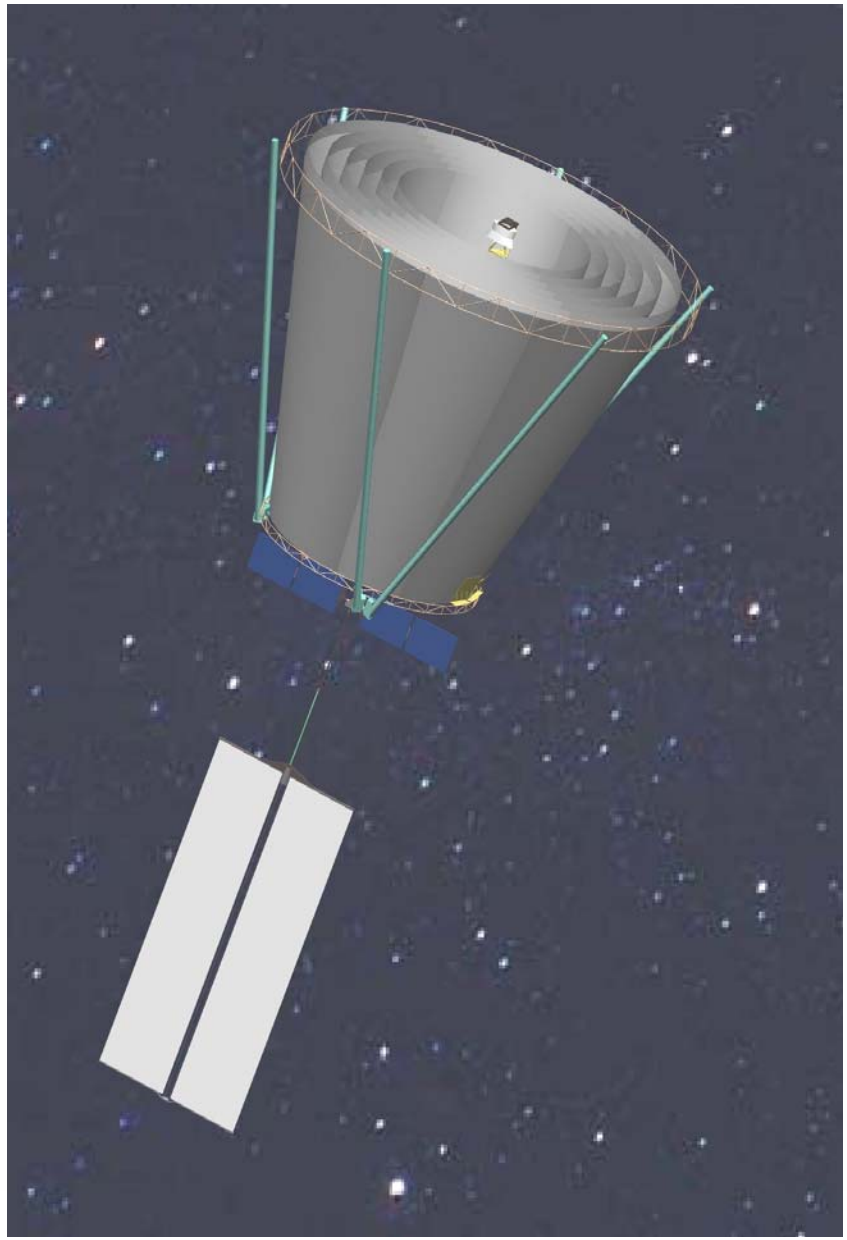
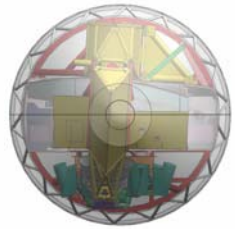


Summary

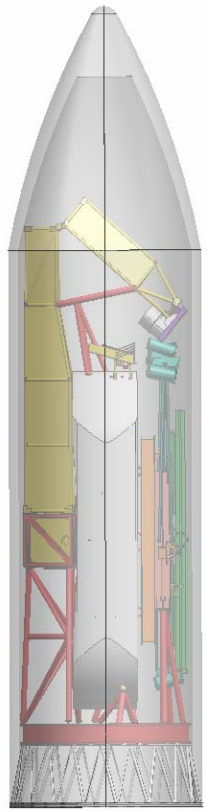
- This presentation summarizes the trade status of TPFC primary mirror shape design
  - Baseline is a 8.0x3.5 meter ellipse
  - Trade consider 8.0x3.0 meter quasi-rectangular shape alternatives that are referred to as “racetrack mirrors”

- Study to date shows adopting a racetrack PM configuration can provide substantial system throughput gains
  - Starlight suppression system is 33% more efficient
  - A 8x3 meter racetrack PM has about 8% more collecting area
  - The combination enables that TPFC can detect and characterize planets in <u>half the time</u> than the current baseline

Racetrack PM Trade Study

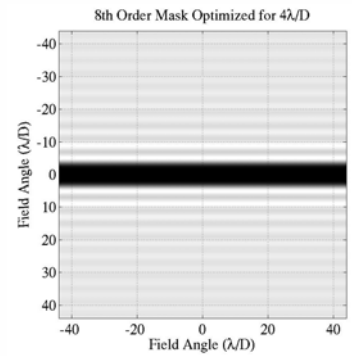


- Motivation
  - Potential to improve corongraph throughput
    - Rectangular PMs well matched to linear occulters
  - Reducing spacing between PM and SM tower
    - Creates volume for launch support structure
- Constraints on mirror shape/size
  - Mirror manufacturability - limited to D < 8.3m (current facilities)
  - Inner diameter of launch shroud (4.57m diameter)
  - Mass budget already very tight
- Trade parameters
  - Coronagraph performance (efficiency, sensitivity)
  - Mirror size
  - Mirror performance (stiffness, frequency, gravity sag)

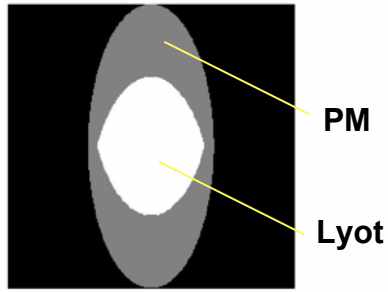


Impact on Coronagraph Efficiency

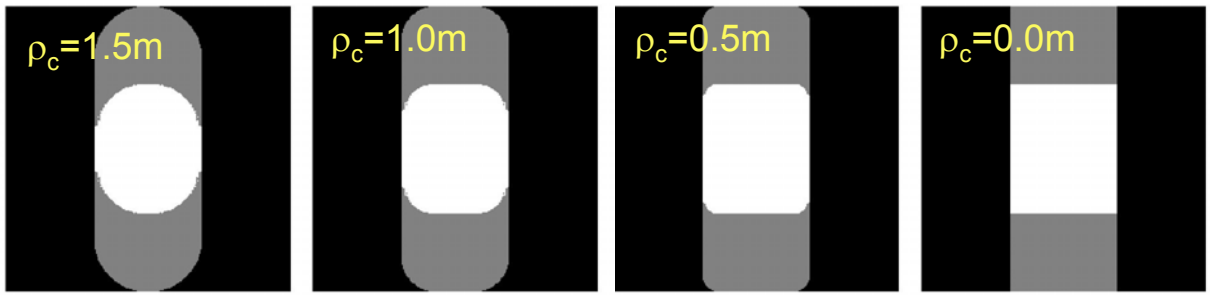
- Modeling Assumptions
  - 8th order mask optimized for 4λ/D
  - λ_o=550nm, Δλ=±50nm



8x3.5m Elliptical



8x3.0m Racetrack



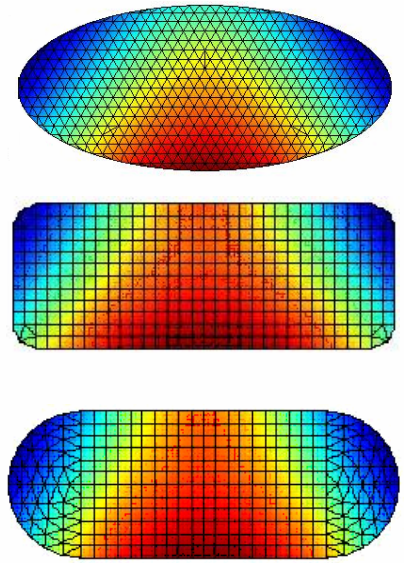
8x3.0m R_{PM}<4

Primary Mirror Shape	PM Area (m^2)	Lyot Efficiency	Net Area (m^2)	FWHM PSF Core Area (mas^2)
8x3.5 Ellptical	21.991	0.340	7.479	1118.6
8x3.0 Racetrack (r_c=1.5m)	22.226	0.406	9.031	942.6
8x3.0 Racetrack (r_c=1.0m)	23.254	0.434	10.083	816.9
8x3.0 Racetrack (r_c=0.5m)	23.837	0.449	10.696	741.5
8x3.0 Racetrack (D=8)	23.410	0.440	10.307	766.7
8x3.0 Rectangle	24.000	0.453	10.875	741.5
Ratio of Rectangle to Ellipse	**1.09**	**1.33**	**1.45**	**0.66**

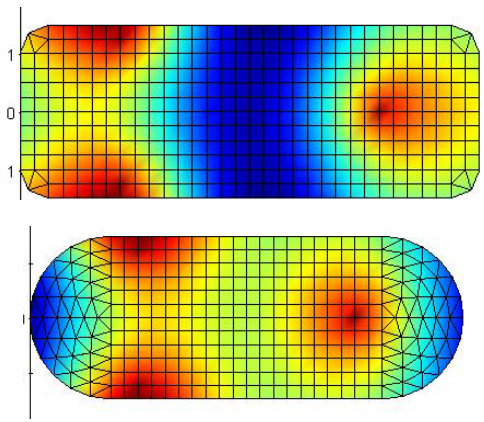
Mounting Optimization

	Natural Freq.	Gravity Sag
	Hz	µm p-v
Elliptical Primary Mirror		
Baseline Mount Placement	25.67	658.30
Optimized about Long Axis	34.32	112.40
Racetrack - 0.5 m Radius Corners		
Bsaeline Mount Placement	22.38	890.10
Optimized about Short Axis	24.02	575.20
Optimized about Long Axis	29.51	100.60
Racetrack - 1.5 m Radius Corners		
Baseline Mount Placement	22.02	914.10
Optimized about Short Axis	29.97	470.40
Optimized about Long Axis	33.01	135.30

Gravity Sag for Baseline Mount Placement



Gravity Sag Long-axis Optimization

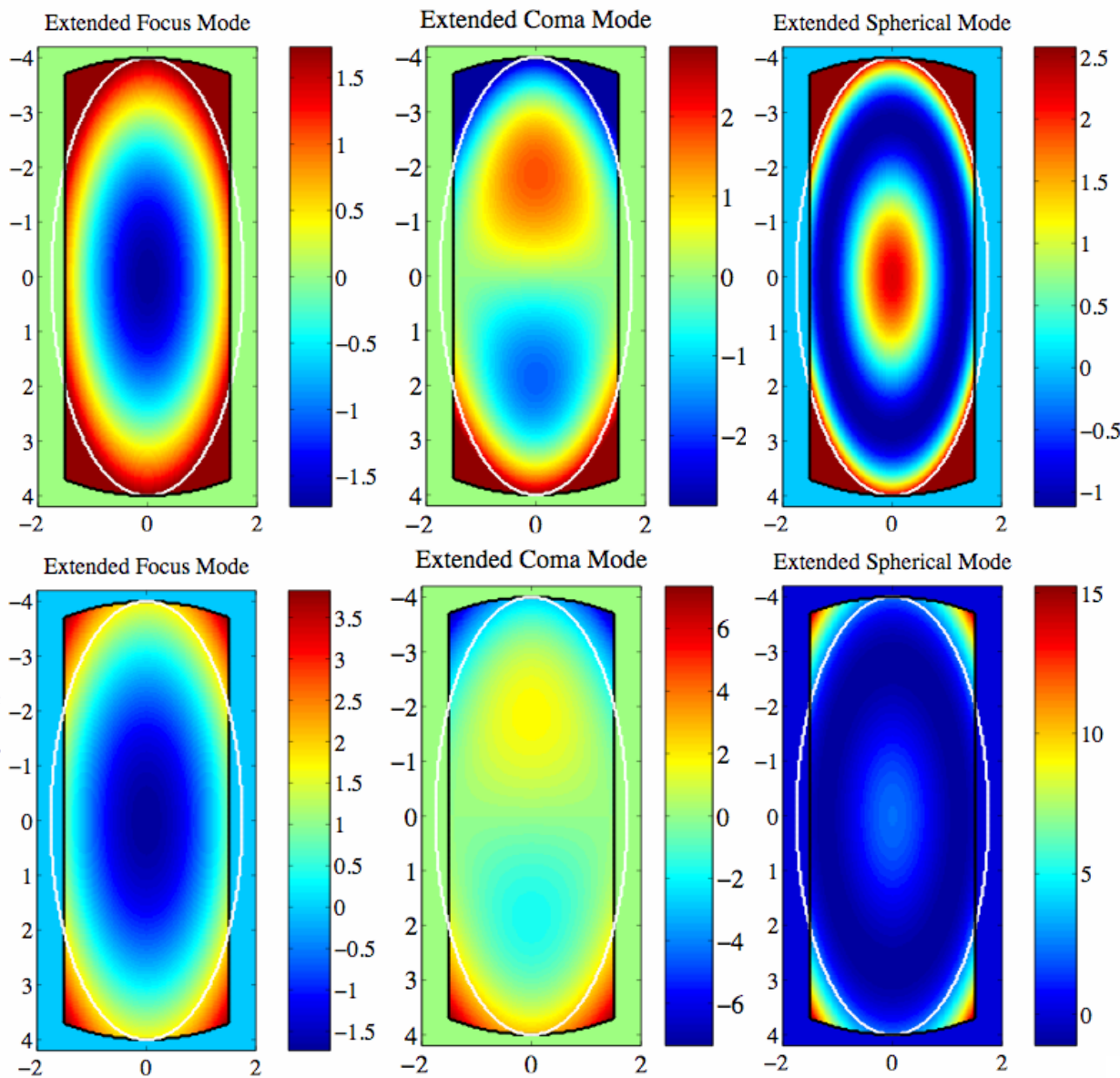


Assumptions:

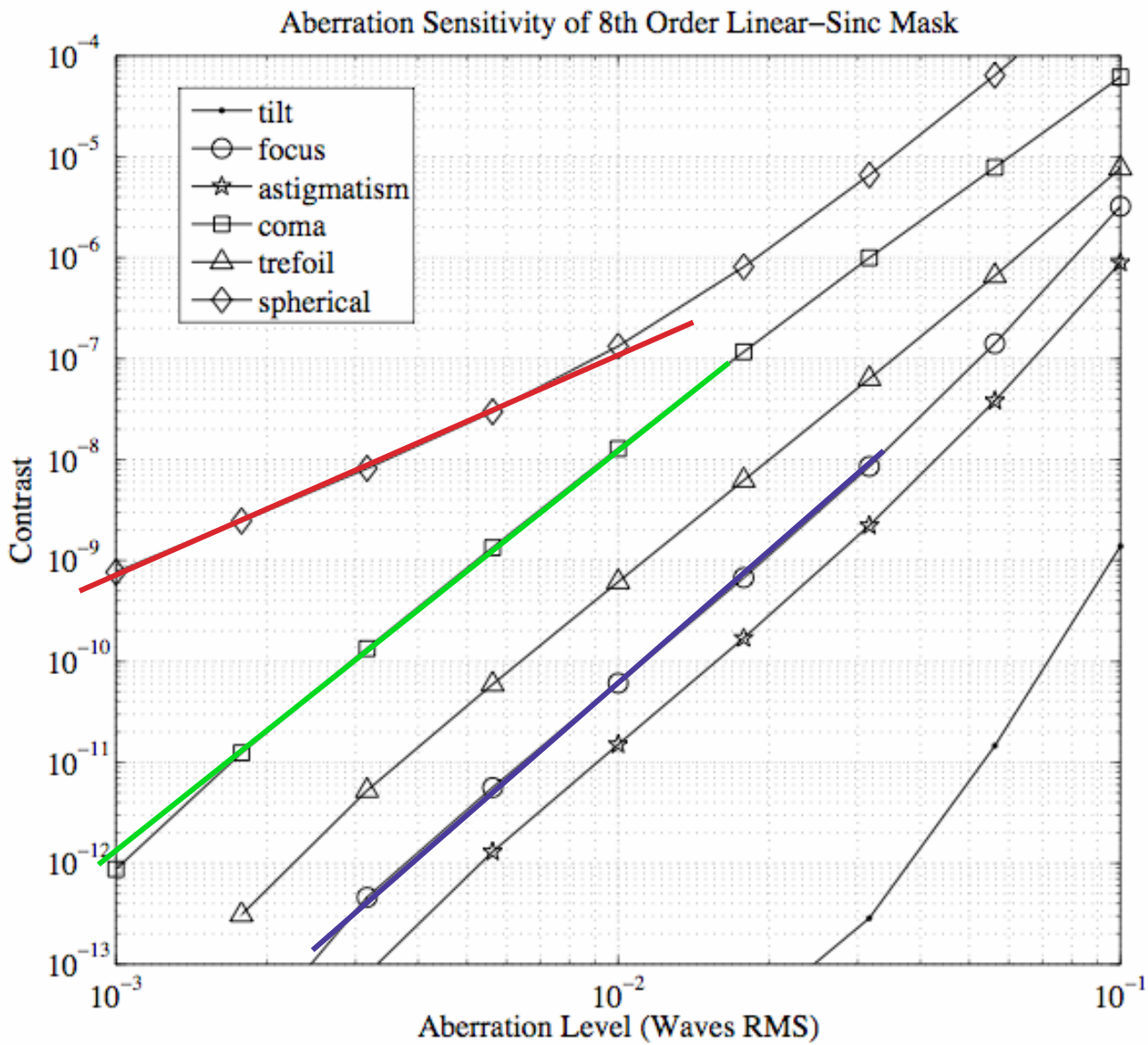
- Flat plate mirrors
- Single point mounting
- Mirror can be supported at nodes
- No thermal or jitter disturbances
- Gravity vector points into the slide

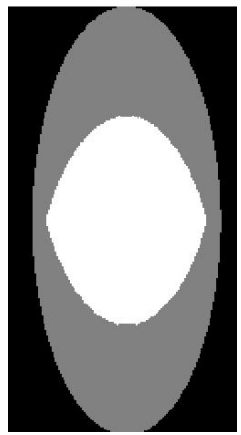
Aberration Sensitivity Analysis

- Error budget based based on elliptical Zernike modes
- To facilitate a direction comparison with a racetrack mirror, the coordinate system is extended beyond the 'unit-ellipse'
  - Violates orthonormality
  - Corners are outside the unit-ellipse and have large deviations which may bias results

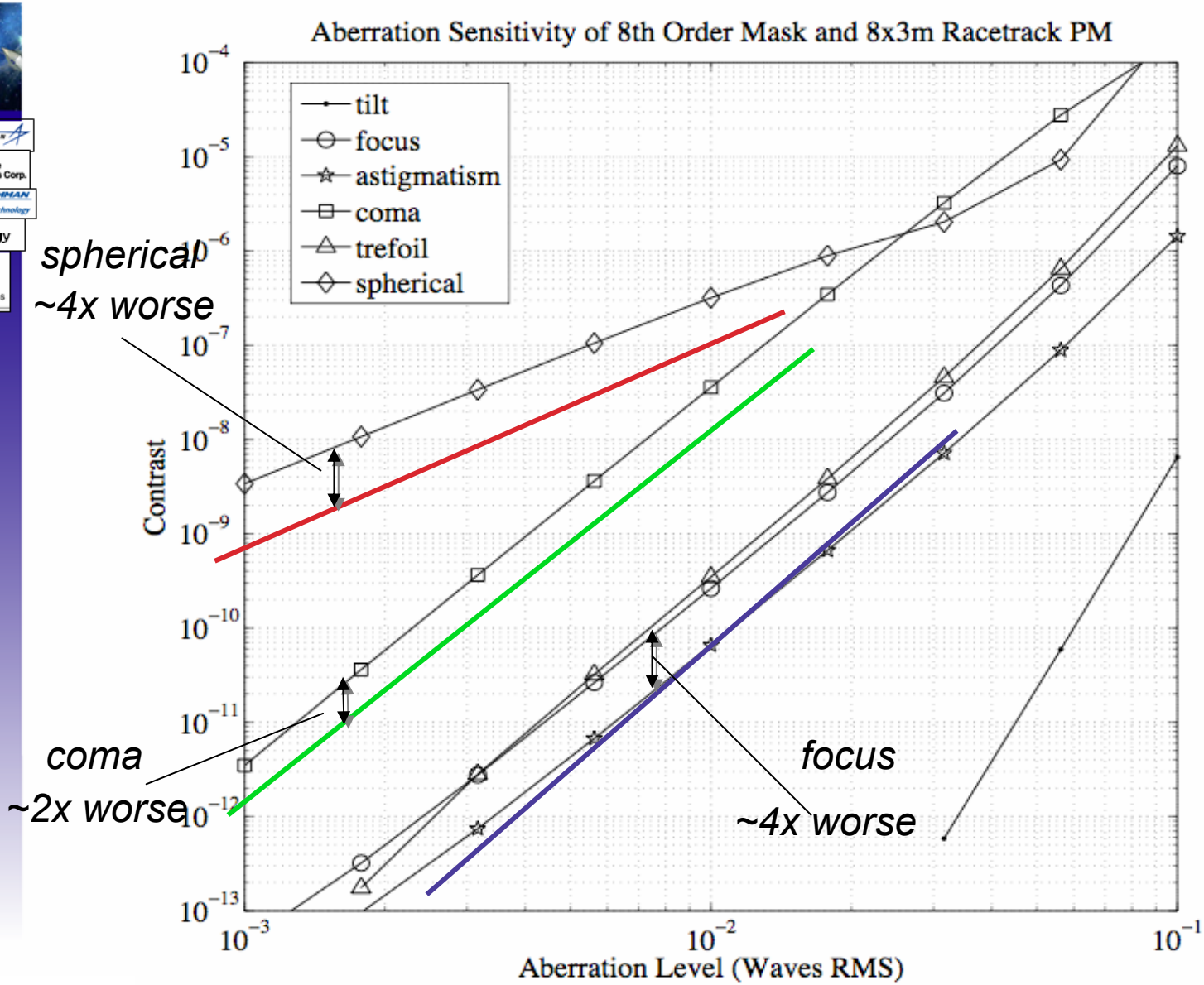


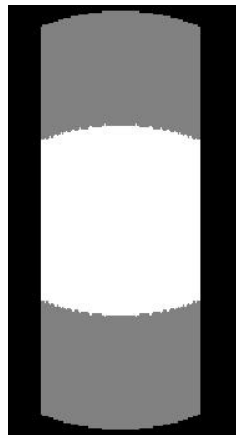
8x3.5 meter Elliptical PM Sensitivity





8x3 meter Racetrack PM Sensitivity





Trade Summary (I)

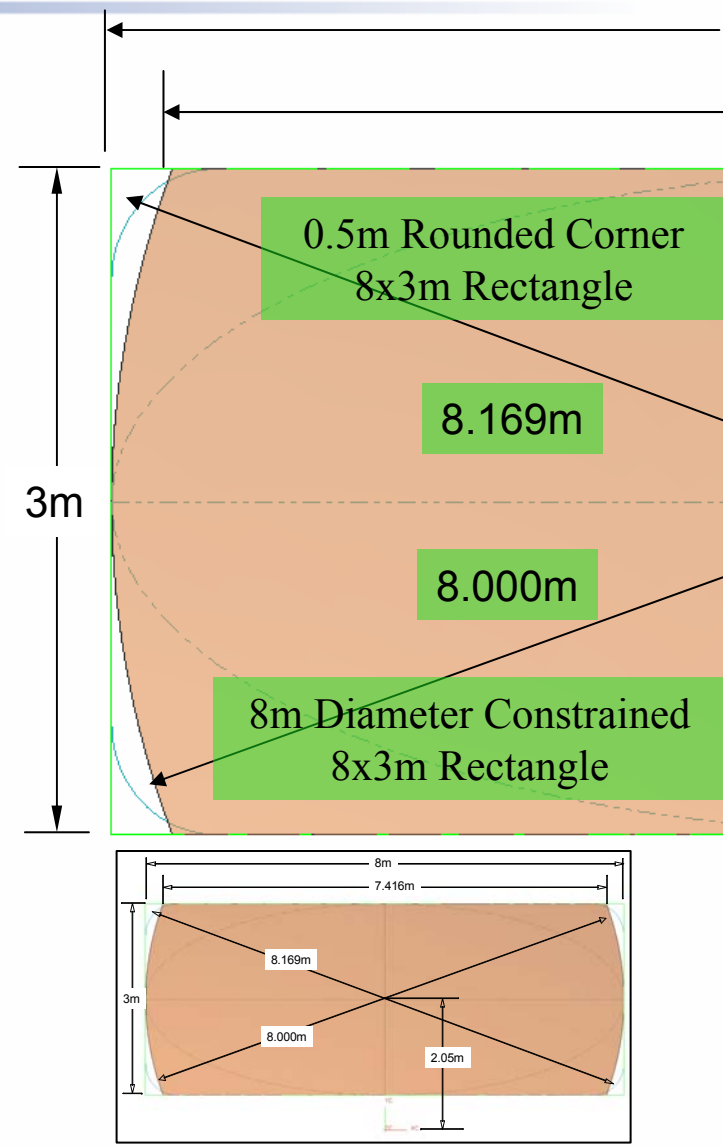
- These two configuration are attractive
  - 40% more effective collecting area for 8% more PM
  - Planet PSF 50% more compact
  - But higher aberration sensitivity

PM + Lyot Stop Shapes

Parameter	8x3.5 Elliptical	8x3 Racetrack rc = 1.5m	8x3 Racetrack rc = 0.5m	8x3 Racetrack D = 8.0m	8x3.0 Rectangle
PM Area (m^2)	21.991	22.226	23.837	23.410	24.000
Lyot Efficiency	0.340	0.406	0.449	0.440	0.453
Net Collecting Area (m^2)	7.479	9.031	10.696	10.307	10.875
FWHM PSF Core Area (mas^2)	1118.600	942.600	741.500	766.665	741.500
Optimized Fund. Freq (Hz)	34.320	33.010	29.510		
Optimized Grav Sag (µm pv)	112.400	135.300	100.600		
Focus Required for 1e-10	1.00E-02			2.50E-03	
Coma Required for 1e-10	3.00E-03			1.50E-03	
Spherical Required for 1e-10	1.80E-04			9.00E-05	

Trade Summary (II)

- Pros
  - TPFC can operate 2x faster!
  - Narrower short axis is more enabling w.r.t. mechanical design
- Neutral
  - Manufacturability
  - Gravity Sag
- Cons
  - 2-4x more sensitive to aberrations
  - Heavier PM
    - 8x2.8m would be about the same as baseline
- To Do
  - Evaluate the net efficiency versus aberration sensitivity impacts upon error budget and completeness



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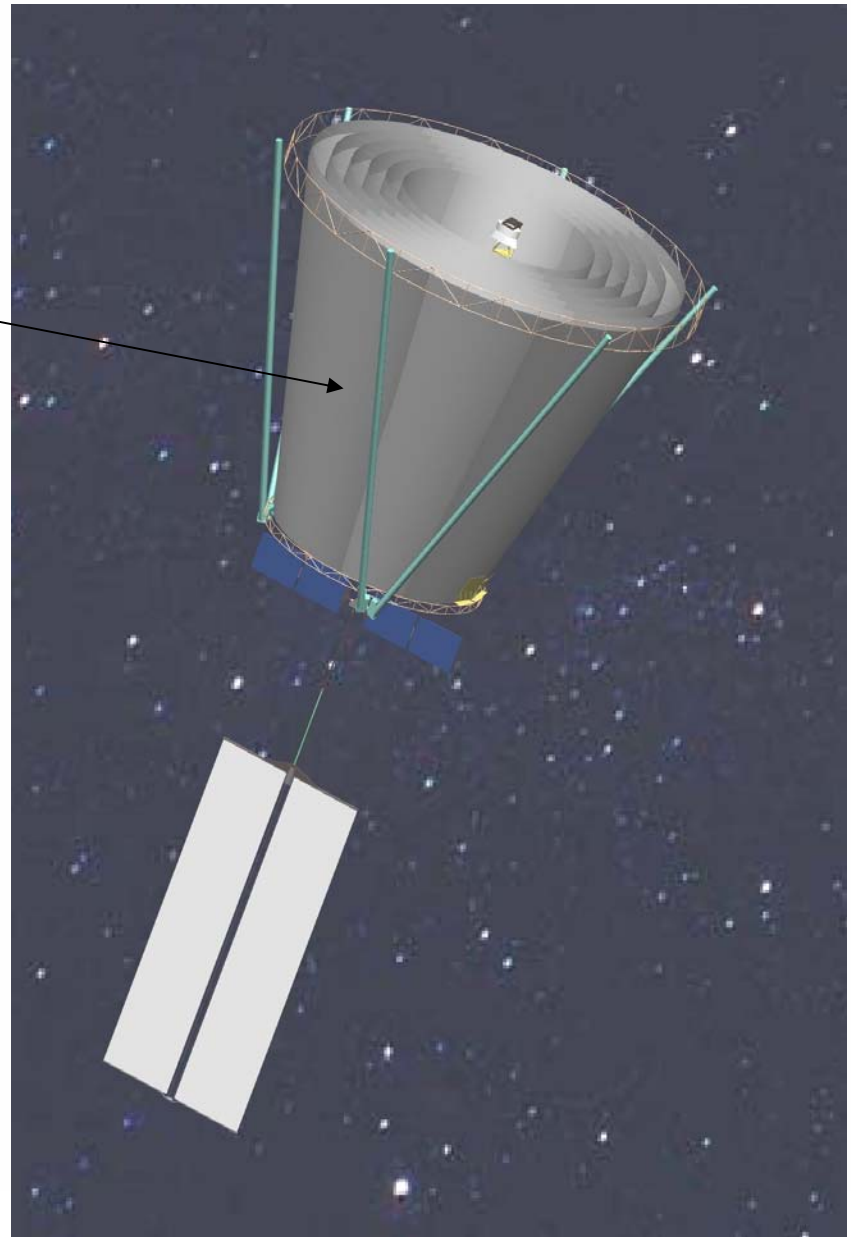
Sunshade Trade Study

'sugar-scoop' vs baseline sunshield thermal performance



presented by
Terry Cafferty

Contributors:
Siu-Chun Lee
Eug-Yun Kwack

11-12 July 2005

'sugarscoop' sunshield, an alternative to our baseline conical shade

- the 'sugarscoop' may be easier to deploy, especially taking into account our fixed passive radiators

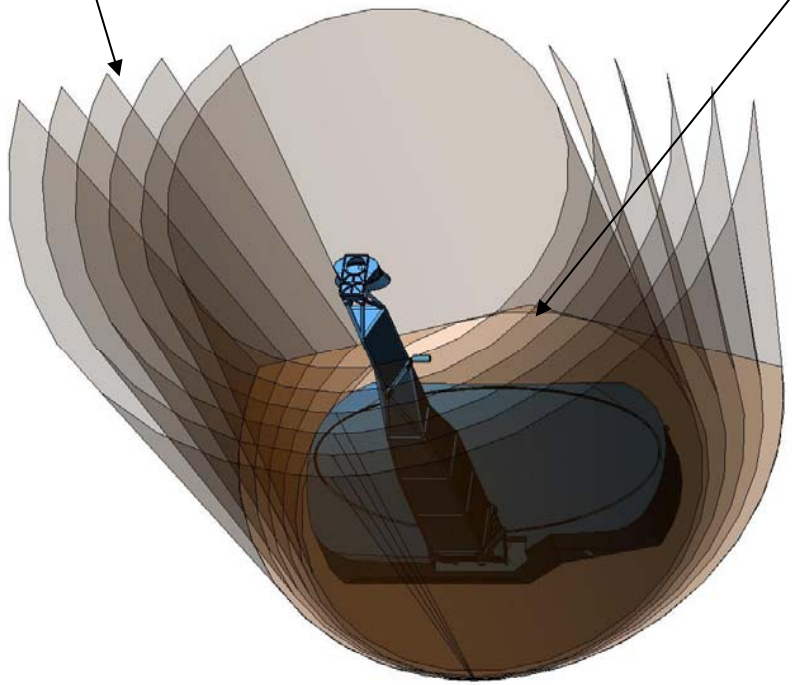
- so we're doing a top-level thermal performance comparison between the 'sugarscoop' and our baseline conical configuration

- simple models include
  - sunshield
  - circular, continuous baffle
  - circular primary mirror
  - black boundary behind PM

- performance metric is steady-state dither-induced, radiatively driven dT in 'primary mirror' surface

'sugarscoop' shields flare circumferentially as well as axially, implying better rejection of perturbing solar energy

radiator location (under baffle base)



'sugarscoop' idea originated with Northrop Grumman Astro Research

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solar angle dither cases

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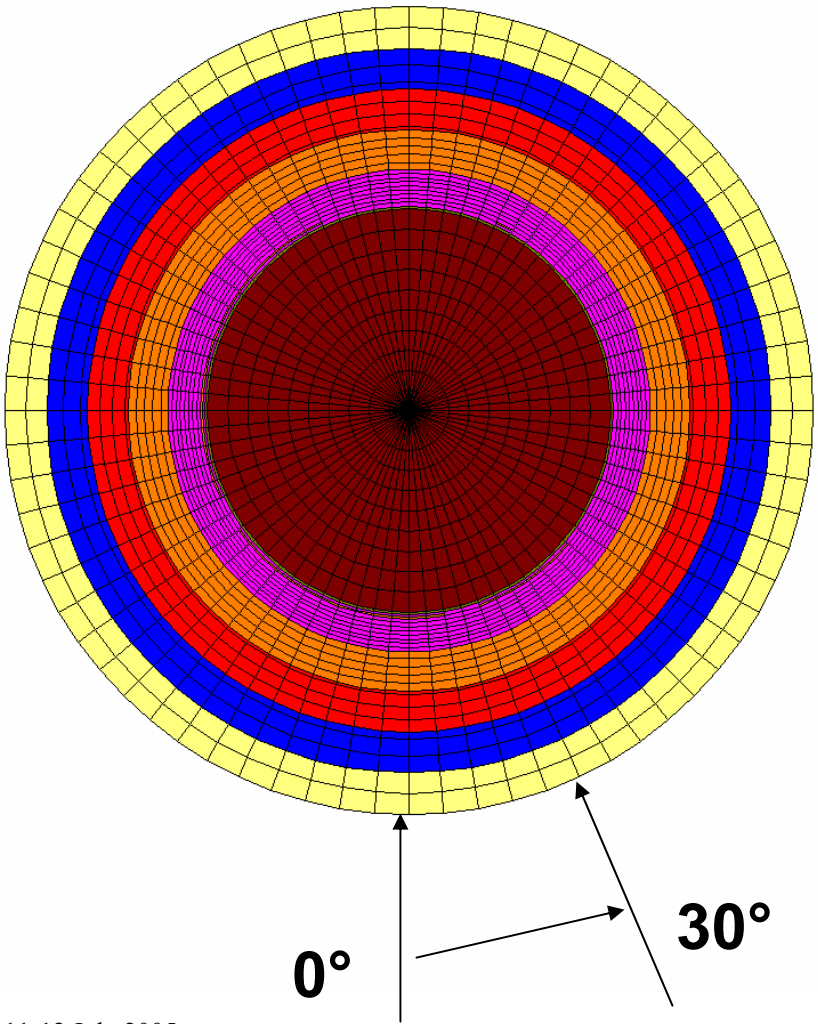
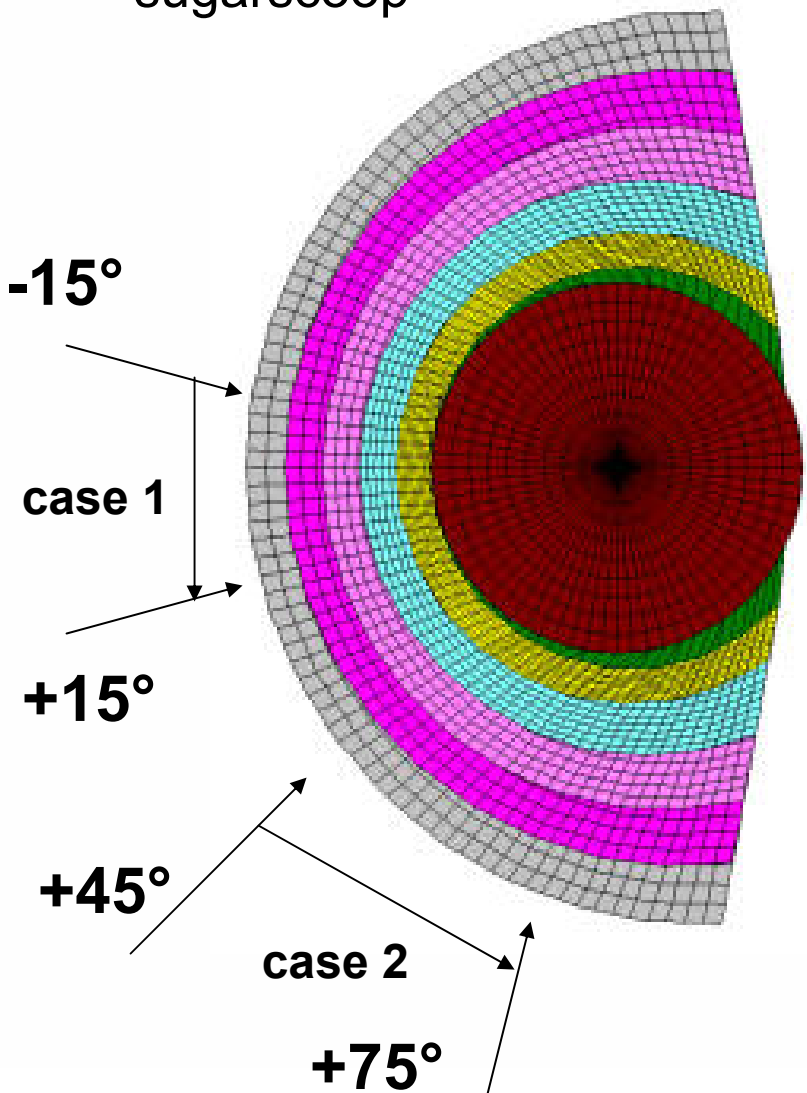
baseline



sugarscoop



Sunshade trade study

preliminary conclusions

- 'sugarscoop' performance appears to be as good as the baseline, consistent with intuition

- analytical mirror dT results are not totally convincing, so we are…

  - comparing results with earlier benchmarking models

  - exploring the limits of temperature prediction precision, (predicted primary mirror temperature changes ~ 1 μK)

  - exploring predictive consistency across different commercial thermal analysis codes

  - verifying the importance of controlling our own thermal analysis code, and correlating models with testbed measurements

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Mass Reduction Trade Studies

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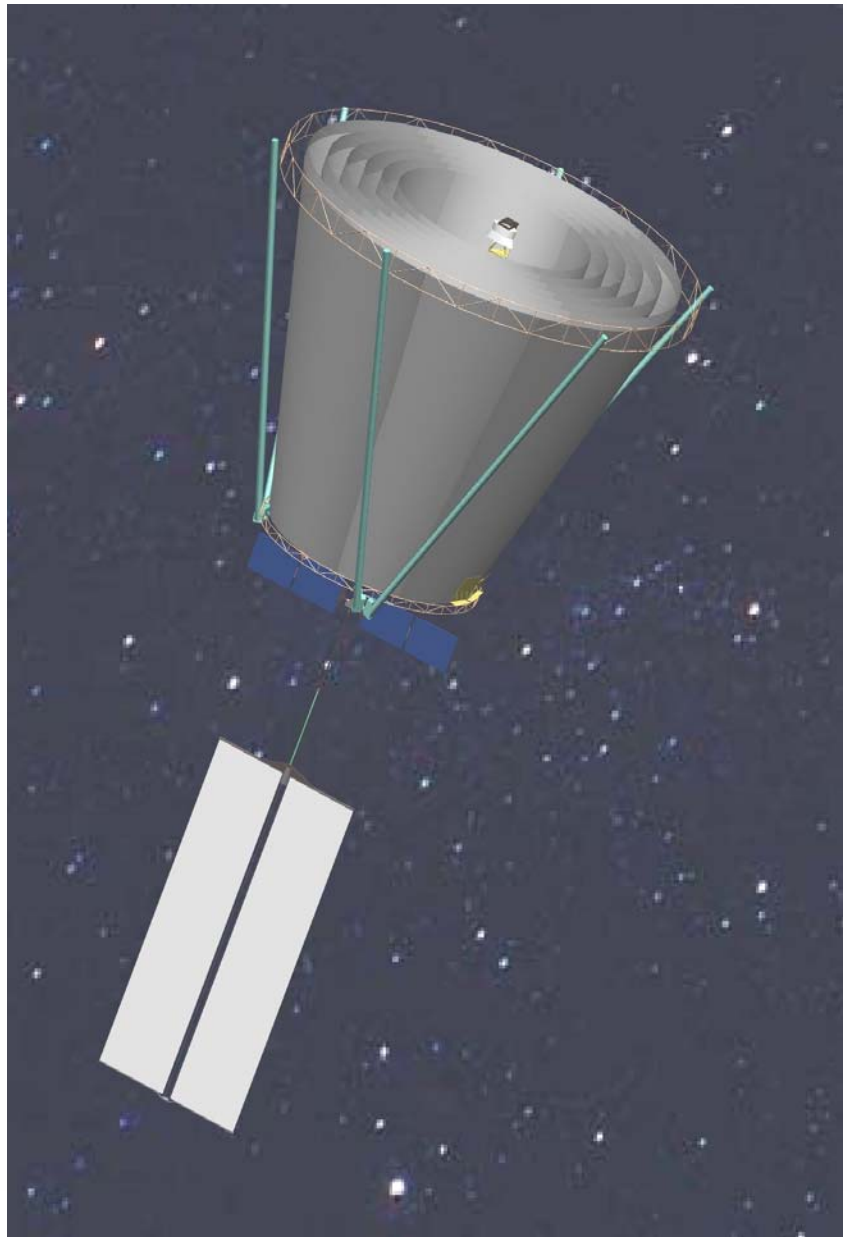


Introduction

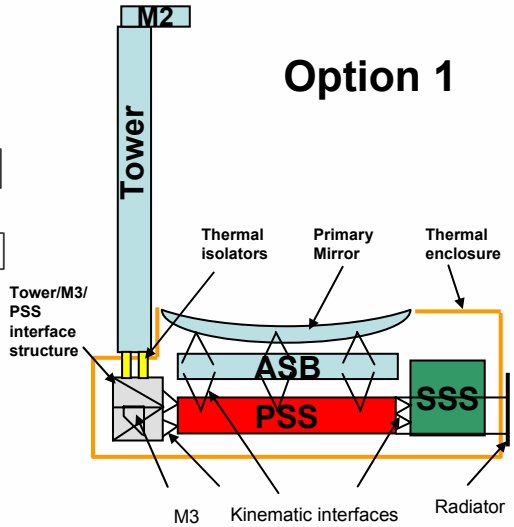
- Current launch mass margin is below suggested JPL guideline for entry into Phase B of 30%
  - % Margin=(Launch Vehicle Capability-Nominal Estimate)/Launch Vehicle Capability x 100
- Self imposed Pre-Phase A launch mass margin goal of >35%
- Need to identify areas in design where mass can be reduced

Trades

- Trades identified in FB1 configuration to reduce mass
  - AMS/PSS interface - consider more mass efficient load sharing between AMS and PSS
    - Most effective source to significantly reduce mass and the one of the largest system design impacts
  - Secondary mirror assembly – optimize materials and sections
  - Secondary tower reconfiguration
  - Thermal enclosure – lattice structure
  - Solar array vs Ultraflex – Ultraflex may be lighter and more compact
  - Solar Sail – consider ISS solar array type deployment for sail area control
  - Reaction wheels – smaller reaction wheels will also save volume
  - Launch support structure - reconfigure to pass all loads through PSS only

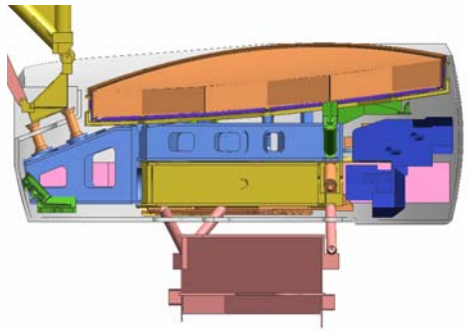
AMS/PSS Interface Options

Option 1



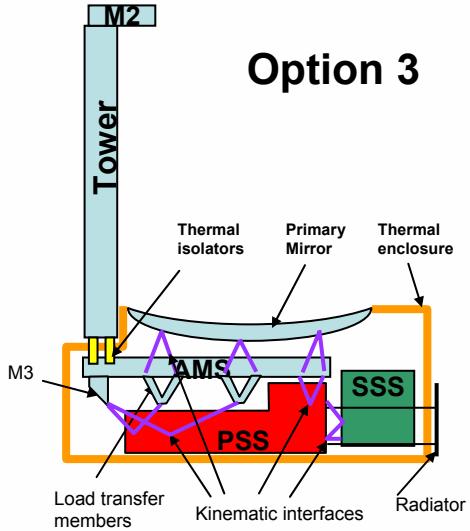
a) Reduce AMS to simply support the auxiliary components of mirror (ie, LD5 boxes, thermal petals, aperture stop, etc) and pass mirror loads straight to PSS
b) Kinematically attach tower/M3 assembly, primary mirror assembly, and instruments independently to PSS.

Option 2



a) Optimize FB1 AMS sections
b) Kinematically attach OTA to PSS.

Option 3



a) Reduce AMS to simply support the auxiliary components of mirror (ie, LD5 boxes, thermal petals, aperture stop, etc) and interface to tower and M3. Pass OTA loads to PSS
b) Kinematically attach OTA and instruments independently to PSS.

Bottom Line

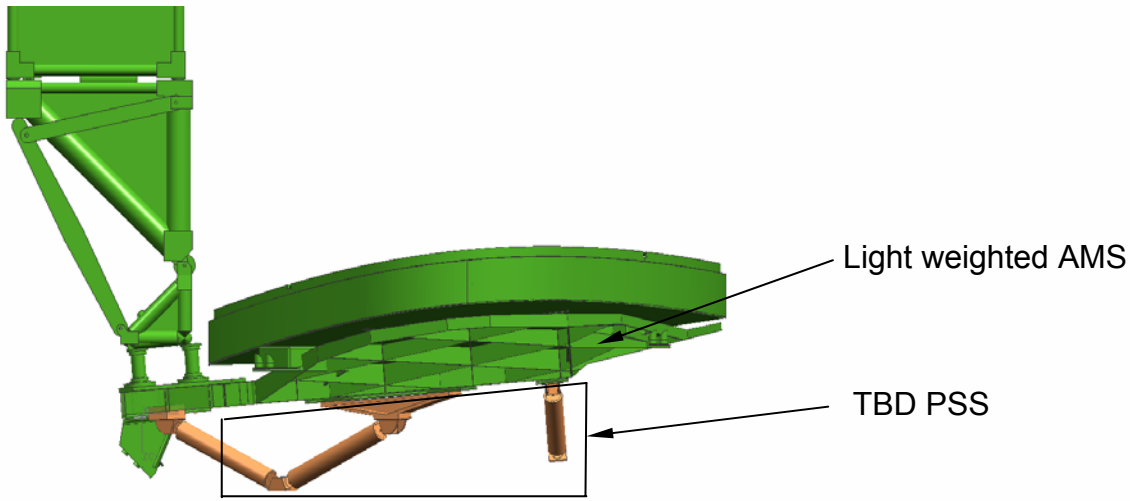
-Impacts to OTA I&T, will require OTA realignment after I&T and a PSS simulator for I&T
-no over-constrained components and mass efficient sharing of loads

-AMS is still stiffer and more massive than required for flight
-Is a single interface between AMS and PSS, no over-constrained components and favorable to I&T (no PSS simulator needed for I&T, no realignment)

-May require OTA realignment after I&T and a PSS simulator for I&T
-is a single interface between AMS and PSS, no over-constrained components, mass efficient load sharing, and favorable to I&T

Summary

- There are several trades identified and areas in the FB1 design where mass reduction is possible
- A preliminary AMS/PSS reconfiguration based on Option 3 could possibly yield ~40% mass reduction of current AMS mass. Work in progress.
- Can likely reduce the system mass to attain a >35% launch mass margin for FB2



Exploring AMS/PSS Concept 3 to understand the load paths, mass and volume impacts on trade space

Lockheed Martin
Ball Aerospace & Technologies Corp.
Northrop Grumman Space Technology
TC Technology
nightsky systems

TPF Terrestrial Planet Finder

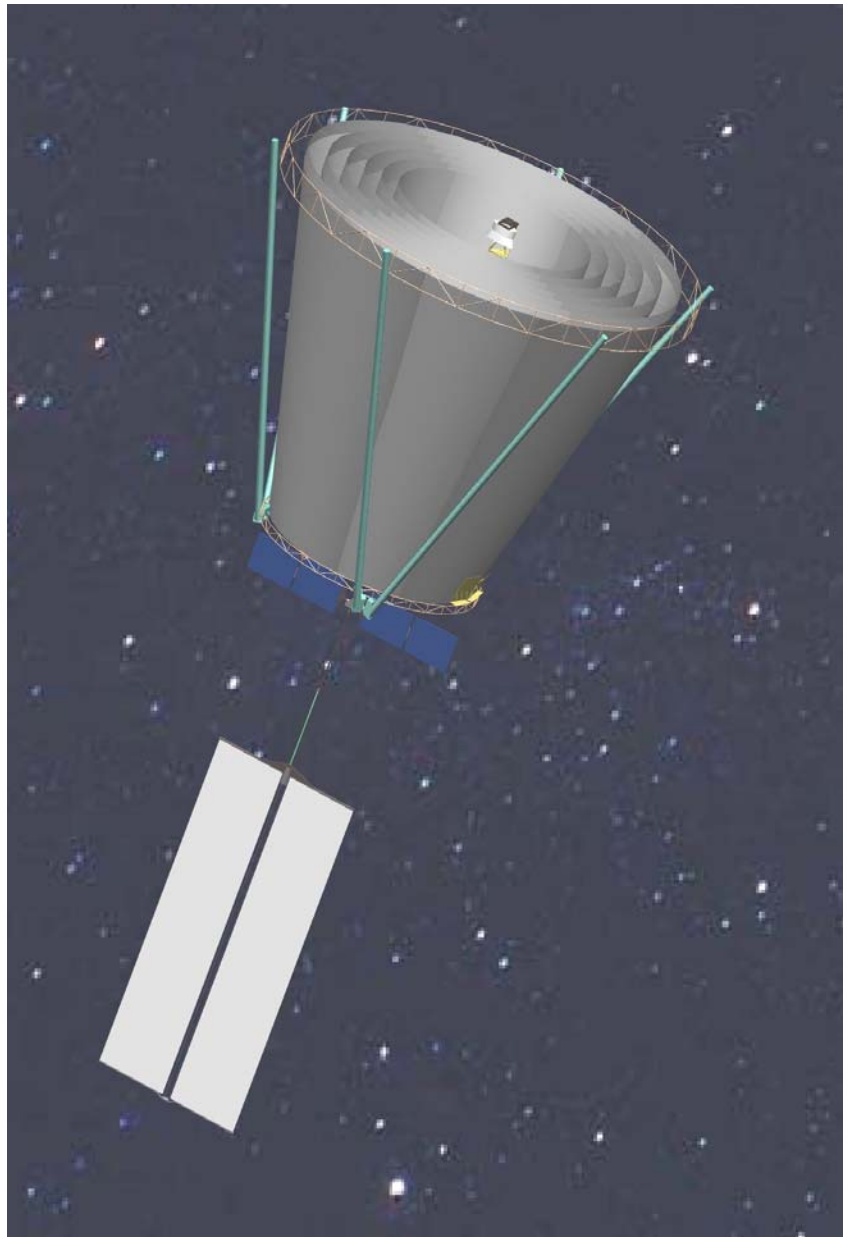
OTA Thermal Trade Study

Open/Closed Back PM

Louis Fantano

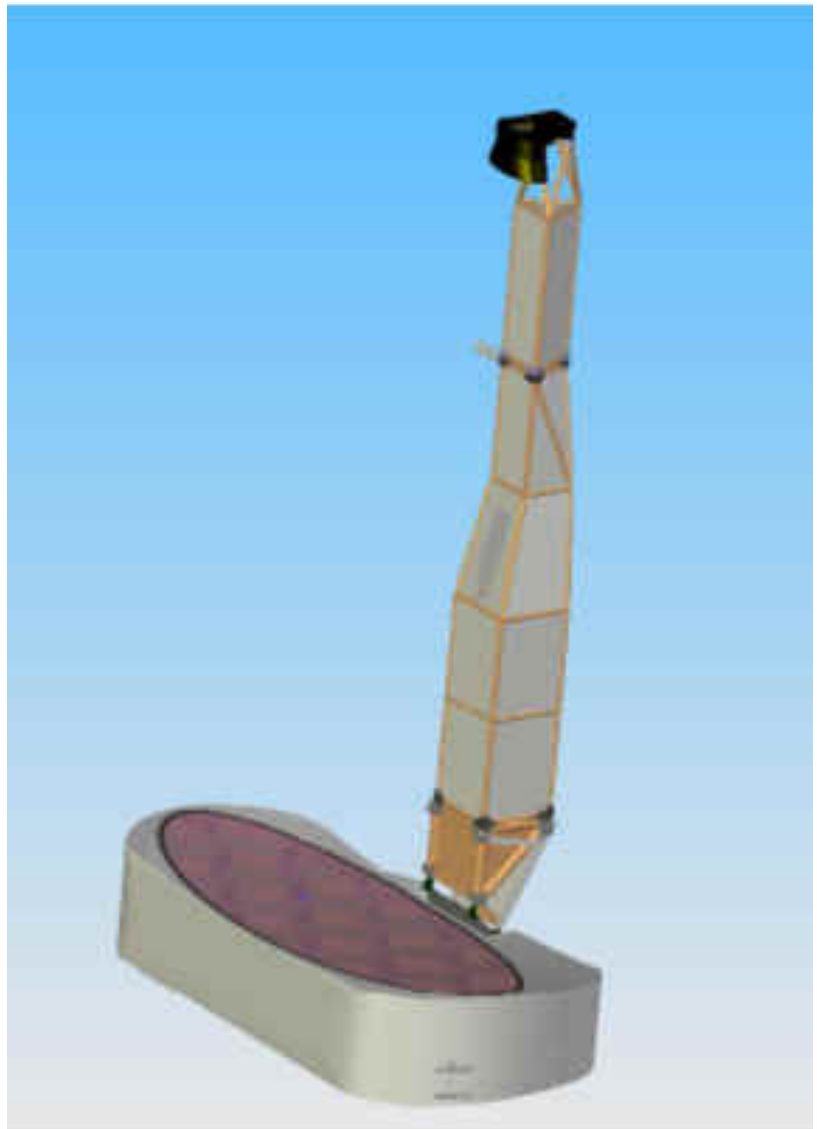
Contributors:
Sharon Peabody
Swales Aerospace

11-12 July 2005



Presentation Outline

- Study Purpose
- Analyses Plan
- Open Back Model
- Closed Back Model
- Preliminary Results
- Planned Future Activity



Study Purpose

- **Provide data to Optics Lead to Discern whether thermal discriminators are significant in the selection of open versus closed back primary mirror designs.**
- **Perform comparative thermal analyses with extremely detailed analytical models to determine PM susceptibility to:**
  - **Transient induced perturbation originating in front of the PM**
  - **Transient induced perturbations originating behind the PM.**
- **Translate these effects to PM optical figure performance with mechanical and optical analyses.**

Analysis Plan

- Using detailed mirror segment models (Open and Closed Back) and simplified surrounding geometry (total of ~ 8900 nodes) perform a series of Trade Studies with varying perturbation schemes
  - Two different thermal solvers used (Sinda/Fluint and TMG)
    - Due to FEM nature of mirror portion of model, TMG solver may be better optimized for solution time and accuracy concerns
    - Comparison of results from both codes
      - If results show adequate agreement and TMG shows a significant improvement in solution time, TMG can then be used in future runs

Perturbation Type	Open Back Low-ε Core	Closed Back High-ε Core	Open Back High-ε Core
1°C Sunshield Perturbation	•√	•√	•√
10mK Sunshield Perturbation	S - eval.	S - eval.	S - eval.
1°C Rear Heater Zone Perturbation	•√	•√	•√
10mK Rear Heater Zone Perturbation	•√	•√	•√

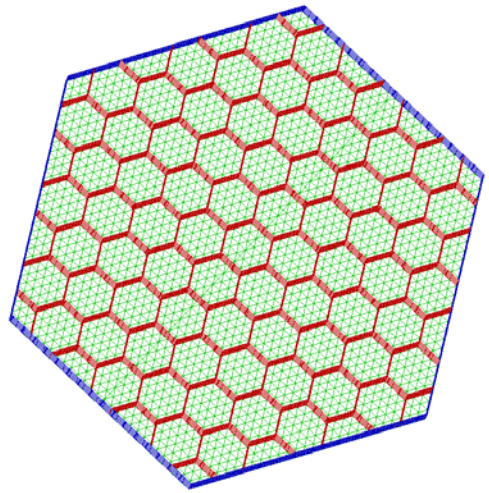
•√ Solution using Sinda/Fluint and TMG

S - eval: Evaluate results from Sinda/Fluint and determine if additional analysis in TMG required

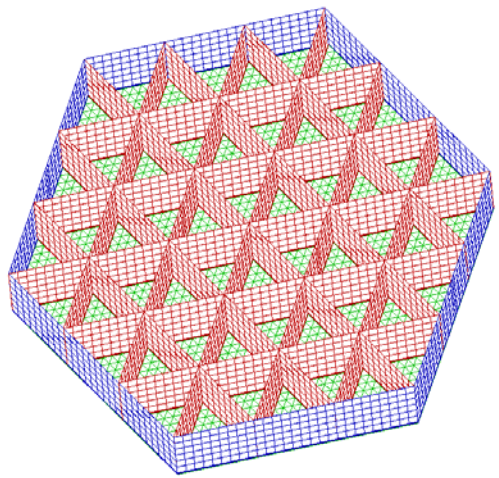
- Update thermal models using more flight-representative V-Groove Sunshield
  - Place mirror segment in 2 different spatial locations (representing approximate mirror center and at mirror perimeter along the major ellipse axis)
  - Repeat analysis cases of interest as defined above
  - Goal to evaluate effects of location on calculated temperature gradients and temporal stability associated with each of the three proposed mirror designs

Thermal Model – Segment Details

- Assumptions
  - Single segment represents entire mirror
  - Closed Back design can only have high ε core
  - Open Back design built with low and high ε core to discern any potential advantages
- Segment models derived directly from NASTRAN structural model with no changes to element mesh
  - Streamlines process of mapping for thermal distortion analysis



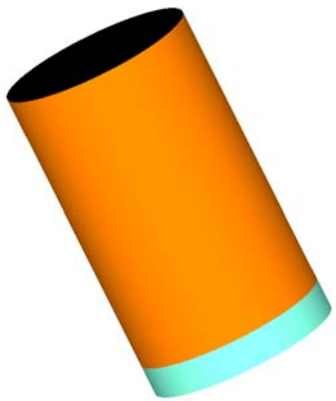
Closed Back Segment Model
(Rear Facesheet Removed)



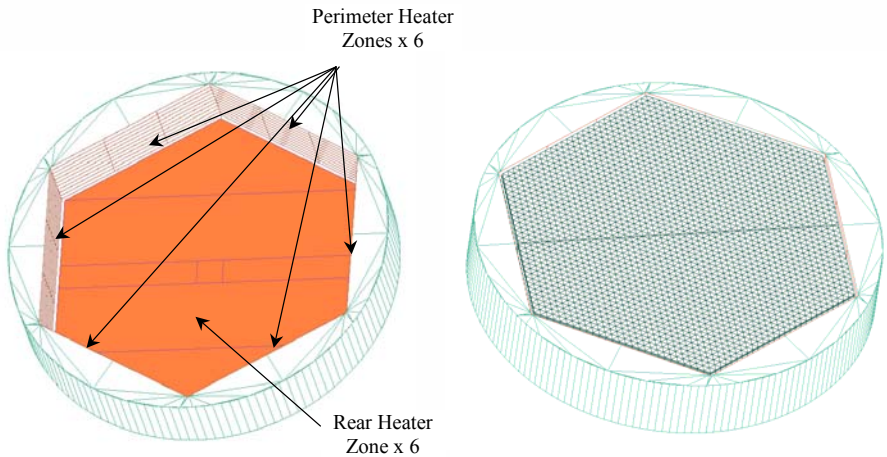
Open Back Segment Model

Thermal Model –Details

- Assumptions
  - Single Sunshield surface around mirror segment modeled
  - 6 Perimeter Heater Zones (with 3x10 surfaces each)
  - 1 Rear Heater Zone (Divided into 7 separate surfaces)
  - Modeled as boundary surfaces (constant temperature) to simulate desired heater control temperature
    - Surface subdivision and control temperatures can be modified as necessary for future analyses
  - MLI Enclosure
    - Surfaces facing segment core – constant temperature @ 20°C



Sunshield Inner Surface and MLI Enclosure Exterior



Perimeter and Rear Heater Zones, Mirror Segment and MLI Enclosure

Preliminary Results

- Analysis Cases Completed by 16:00 Wednesday 7/20/05

Model	1°C Sunshield Perturbation Sinda/Fluint	1°C Rear Perturbation Sinda/Fluint	10mK Rear Perturbation Sinda/Fluint
Open Back, Low ε Core	Y	Y	Y
Closed Back	Y	Y	Y
Open Back, High ε Core	Y	Y	Y

*** Note that the 10mK Sunshield Perturbation Cases **were not** performed in either Sinda/Fluint or TMG due to limited response seen from 1°C Sunshield Perturbation results

Model	1°C Sunshield Perturbation TMG	1°C Rear Perturbation TMG	10mK Rear Perturbation TMG
Open Back, Low ε Core	Y	Y	Y
Closed Back	Y	Y	N
Open Back, High ε Core	N	Y	Y

*** Note that the 10mK Sunshield Perturbation Cases **were not** performed in either Sinda/Fluint or TMG due to limited response seen from 1°C Sunshield Perturbation results

- Currently, thermal model case matrix is at ~90% complete
- TMG Cases (with a specified DT) found to run markedly faster than Sinda/Fluint (using automatic timesteps) with little impact to solution agreement (discussed on following chart)
- Shorter TMG solution time will require less time to complete the remaining TMG runs (2 hours per TMG run vs. 10-12 hours for Sinda/Fluint)
- Full data comparison (Sinda/Fluint to TMG) and other post-processing to begin as equivalent cases are completed
- Anticipating completion of 2 remaining TMG runs by 12:00 Thursday 7/21/2005

Preliminary Results - 2

- Comparison of Initial Steady State Results from Sinda/Fluint and TMG for Closed Back Model, 1°C Sunshield Perturbation Case
  - Representative mirror nodes chosen and Sunshield surfaces set as boundaries tabulated to verify correct model execution

Node Description	SS			Beginning of Transient			2 hrs		
	SF	TMG	Δ (TMG-SF)	SF	TMG	Δ (TMG-SF)	SF	TMG	Δ (TMG-SF)
Center or Mirror	293.35967	293.35960	-0.00007	293.35967	293.35960	-0.00007	**293.35993**	**293.35993**	**0.00000**
Mirror Corner	288.43824	288.43822	-0.00002	288.43824	288.43822	-0.00002	288.44391	288.44391	0.00000
Sunshield (Near Mirror)	152.02061	152.02060	-0.00001	153.02061	153.02060	-0.00001	153.02061	153.02060	-0.00001
Sunshield	142.90092	142.90091	-0.00001	143.90092	143.90091	-0.00001	143.90092	143.90091	-0.00001
Sunshield	136.04413	136.04412	-0.00001	137.04413	137.04413	0.00000	137.04413	137.04413	0.00000
Sunshield	131.47365	131.47364	-0.00001	132.47365	132.47365	0.00000	132.47365	132.47365	0.00000
Sunshield	127.51901	127.51900	-0.00001	128.51901	128.51900	-0.00001	128.51901	128.51900	-0.00001
Sunshield	123.47242	123.47241	-0.00001	124.47242	124.47241	-0.00001	124.47242	124.47241	-0.00001
Sunshield	118.98495	118.98494	-0.00001	119.98495	119.98495	0.00000	119.98495	119.98495	0.00000
Sunshield	113.57532	113.57531	-0.00001	114.57532	114.57532	0.00000	114.57532	114.57532	0.00000
Sunshield	108.36371	108.36371	0.00000	109.36371	109.36371	0.00000	109.36371	109.36371	0.00000
Sunshield (Space End)	101.61439	101.61438	-0.00001	102.61439	102.61438	-0.00001	102.61439	102.61438	-0.00001

- Above results indicate a maximum delta on segment center of ~26μK (Sinda/Fluint) and ~33μK (TMG) from initial steady state temperature predictions
- Resulting small deltas on segment center prompted decision to not run 10mK Sunshield Perturbation case for any mirror configurations
- Full transient data indicates that segment center transient response has damped out after less than 2 hours

Preliminary Results - 3

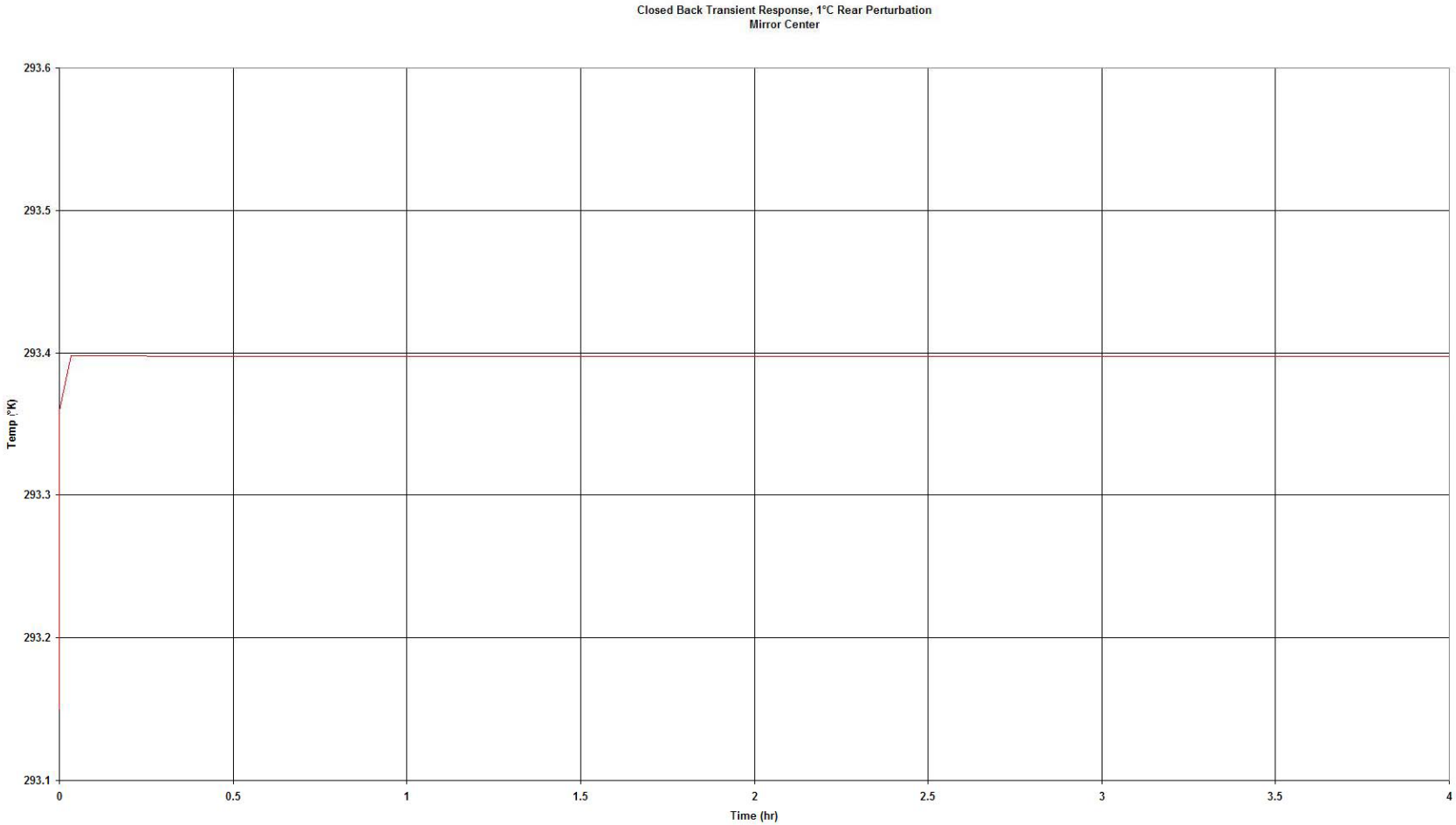
- Transient response of Closed Back segment nodes to 1°C Rear Heater Perturbation Case
  - Representative mirror nodes chosen and Rear Heater surfaces set as boundaries tabulated to verify correct model execution

Node Description	Node #	Node #	SS	Beginning of Transient	2 hrs	4 hrs
			SF	SF	SF	SF
Center or Mirror	100001	FEMAP.100001	293.35967	293.35967	293.39767	293.39767
Mirror Corner	100894	FEMAP.100894	288.43824	288.43824	288.43924	288.43924
Rear Heater Zone (14)	14	RHZ.14	295.14999	296.14999	296.14999	296.14999
Rear Heater Zone (13)	13	RHZ.13	295.14999	295.14999	295.14999	295.14999

- Larger effect on mirror center seen in rear perturbation cases
- Full transient data indicates that mirror center transient response has damped out after less than 1 hours

Preliminary Results - 4

- Closed Back Partial Transient response for mirror center (Sinda/Fluint), 1°C Rear Heater Zone Perturbation Case



Preliminary Results - 5

- Maximum Delta T (° K) for 8 completed cases
- For all three models, when a 1 ° C perturbation on sunshield surface is induced, mirror center response is on the order of μK

Node Description	Maximum Delta (°K)							
	OB Low-ε, 1°C Sunshield Perturbation	OB Low-ε, 1°C Rear Heater Perturbation	OB Low-ε, 10 mK Sunshield Perturbation	CB, 1°C Sunshield Perturbation	CB, 1°C Rear Heater Perturbation	CB, 10 mK Sunshield Perturbation	OB High-ε, 1°C Sunshield Perturbation	OB High-ε, 1°C Rear Heater Perturbation
Mirror Center	2E-05	0.06325	0.00059	0.00026	0.03800	0.00031	0.000	0.02789
Mirror Edge	0.00449	8E-05	0.00000	0.00567	0.00100	0.00000	0.00481	0.00079

- Open Back High-ε core with a 10mK perturbation analysis still pending
- Transient temperature data for cases of interest to be shared with optics team and delivered to structural team for thermal distortion mapping

Planned Future Activity

- Model Updates
  - Representative V-Groove Sunshield as used in JPL provided models
  - "Adiabatic" MLI well formed to close out the enclosure geometry below the primary mirror
  - Mirror segment placed in 2 different spatial locations (approximate mirror center and mirror edge along major axis)
  - Based on results from trade study, determine cases of highest interest

- Analysis Plan
  - Rerun thermal analyses (based on current plan) and evaluate:
    - Effects of location on calculated temperature gradients
    - Temporal stability associated with the three proposed mirror designs