# *Section 7:*

# *Integrated System Description*

(The rest of the TPF System)

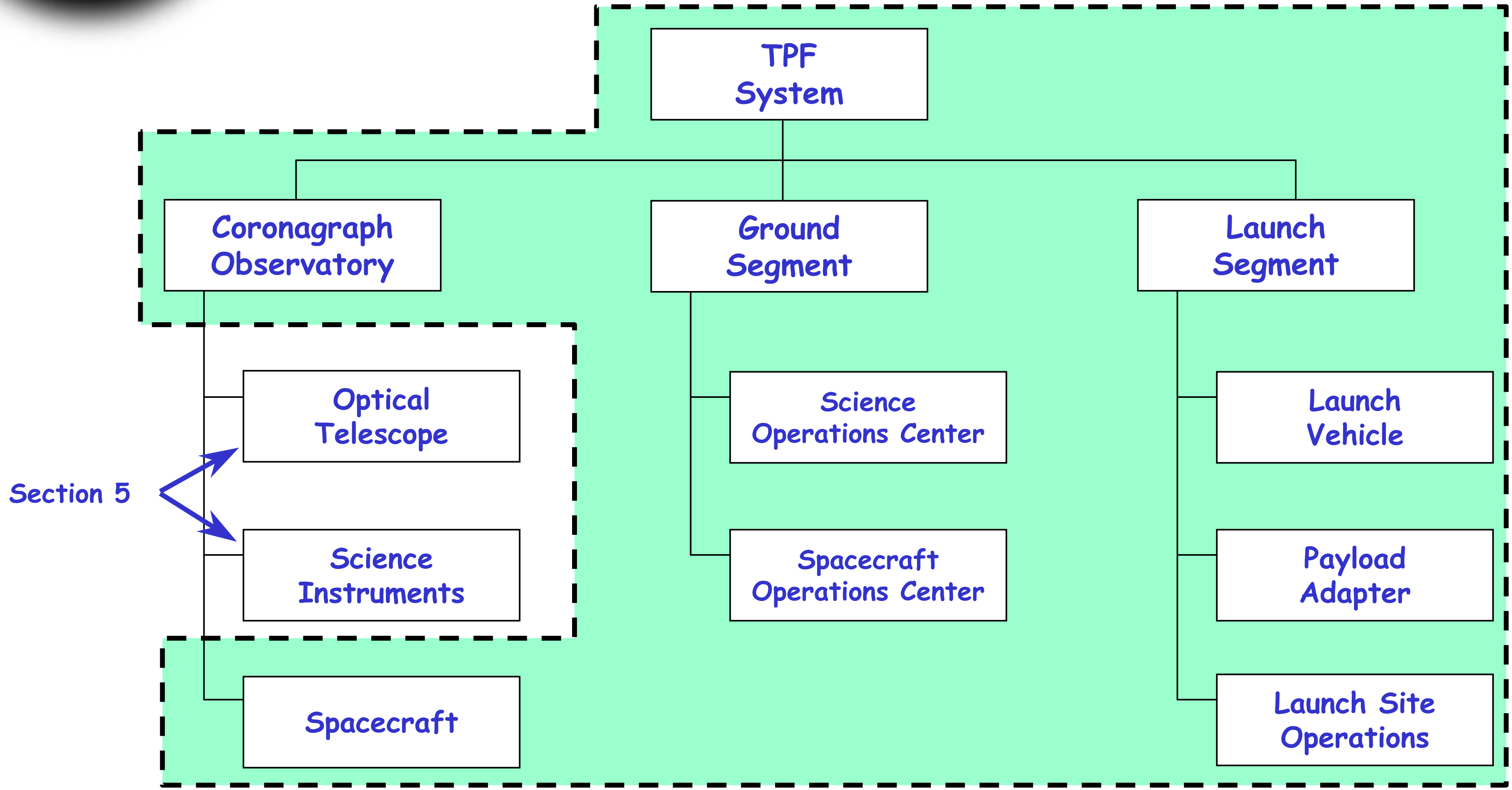
## Kenny Epstein

Spacecraft Description: Structures & Mechanisms, Orbits, Attitude Control, Propulsion, Thermal, Telecommunications, Power, C&DH, Software, Mass, Robustness & Reliability

Launch Segment

Ground Segment

# Major System Constituents of the TPF Coronagraph


TPF System

Coronagraph Observatory

Ground Segment

Launch Segment

Optical Telescope

Science Instruments

Spacecraft

Science Operations Center

Spacecraft Operations Center

Launch Vehicle

Payload Adapter

Launch Site Operations

Section 5

All Major System Elements Evaluated

# *Overview of the TPF Coronagraph Observatory*

Major Features

Optics

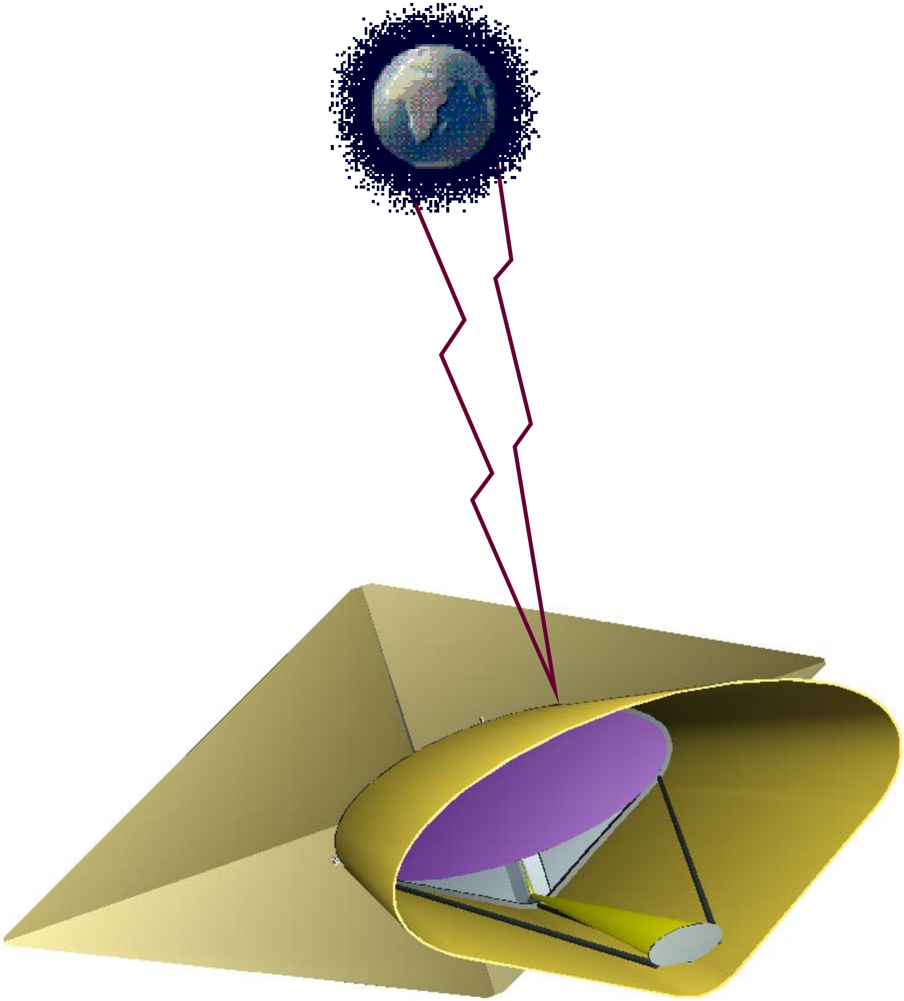
- 10 x 4 Meter Monolithic Primary
- Off Axis Design – very low diffraction
- Adaptive Optics Wavefront Control

Orbit

- Earth Trailing Drift Away
- Stop Drift @ 0.2 AU
- Delta IV H – direct insertion

Other

- Articulated Sun Shield/Array
- 3 Axis Stabilized Spacecraft
- Launch Mass ~6,000 kg
- Power 2.1 KW EOL
- 5 Yr Design Life (10 yrs of Expendables)



# TPF Coronagraph Observatory Science Requirements

- TPF must detect radiation from any Earth-like planets in the habitable zones surrounding ~150 solar type (spectral types F, G, and K) stars within 20pc of Earth. Meet – by 10 x 4 meter very low diffraction adaptive optics design
- TPF must characterize the orbital and physical properties of all detected planets to assess their habitability and characterize the atmospheres and search for potential biomarkers in the brightest candidates. Meet by high spectral sensitivity for Biomarkers in the 0.5 to 0.8 micron band
- 50% of Primary Mission is devoted to Astrophysics. Meet by, optimizing Planet Finding throughput efficiency, thus allowing for Astrophysics within 5 year design life

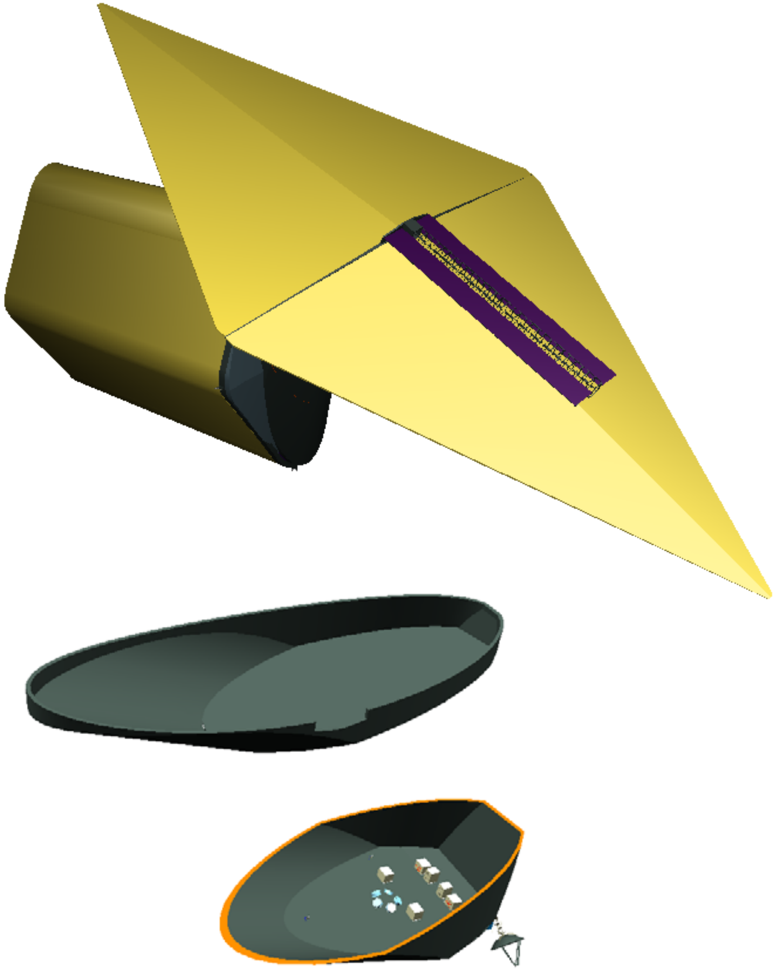
Additional Definitions:

- Primary Mission Design Life of 5 Years, with expendables (propellants, batteries, solar array) sized for 10 years
- Detection is defined as Repeatable observations with SNR of at least 5
- Earth-like Planets are defined as Planets from one-half to twice the radius of Earth
- Habitable Zones is defined as the loci of orbits where an Earth-sized planet would be heated by its star to temperatures permitting liquid $H_2O$ retention at 1 atmosphere pressure (which could involve some planet and atmosphere evolution)

# Overview of the Spacecraft (Bus) Assembly

Major Features

- Fully Redundant Avionics
- 5 Yr Design Life
  - 10 yrs of Expendables - Batteries, Solar Cells, Propellants, Thermal Shields
- Asymmetric Modular Structure
- Articulated Sun Shield/Array
  - For Thermal Gradient Control
  - For Cp to Cm Control
  - For Power
- 3 Axis Stabilized Spacecraft
  - Low Jitter Precision Pointing - Reaction Wheel on Isolators for fine control and Sun Shield for Coarse Control
  - Reaction Wheels for Coarse Re-Pointing between Stars
  - Hydrazine Thrusters for De-tumble, Safing, and for occasional momentum unloading



# Design Drivers for Structures & Mechanisms (SMS)

- Packaging of 4 x 10 Meter Monolithic Primary Mirror
- Packaging and Deployment of Off Axis Secondary Mirror
- Packaging of Observatory in Existing Launch Vehicles (or those currently under development)
- Extremely Low Jitter Requirements, minimize disturbances through structural system
- Extremely Low distortion Requirements, minimize thermal gradients and associated distortions at the nanometer level.
- Mirror actuation & calibration at a nanometer level.
- Packaging of Science Instruments

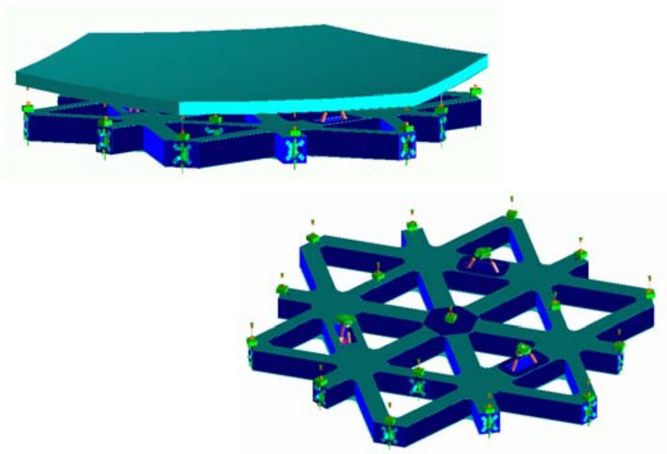
- Integration Assembly and Test (IA&T)
  - Modular Assembly Approach
  - Separate Optical Telescope Assembly (Requiring Stringent Clean Room Requirements)
  - Separate Spacecraft (Bus) Assembly
- Packaging of Standard Spacecraft Services
  - Electrical Power & Distribution System (EPDS)
  - Telecommunications
  - Attitude Determination & Control Systems (ADCS)
  - Propulsion
  - Command & Data Handling (C&DH)

# Implications of Microdynamic Behavior of TPF Coronagraph Structure

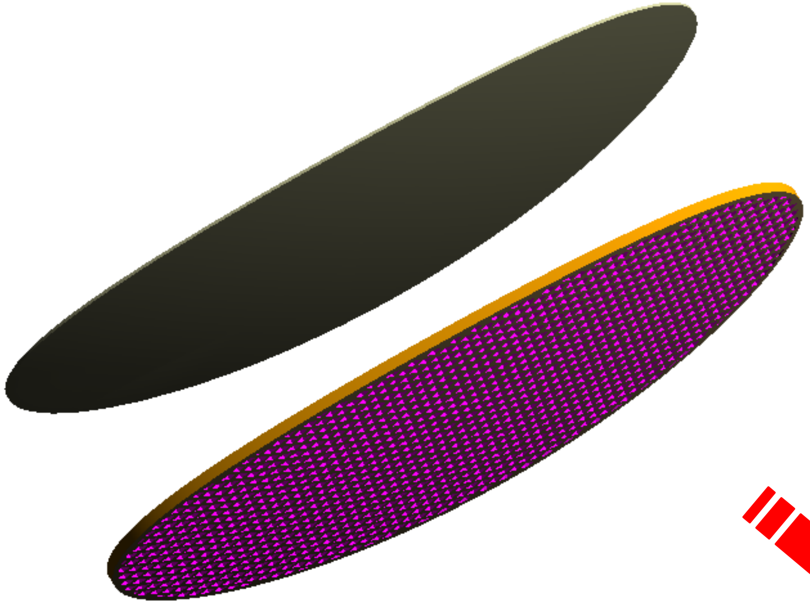
- Integration of the Microdynamic behavior into the Program will be key to meeting the low disturbance demands of the Coronagraph
- Develop sufficiently detailed disturbance Requirement flowdown from optics to mechanisms
- Design an integrated system
  - Integrate joint behavior into the overall observatory structure.
  - Define Load Paths that minimize Microdynamic effects.
  - Define Maneuvers and Environments that minimize Microdynamic effects
    - No Thermal Snap
    - Sufficiently Smooth Slew Maneuvers
- Develop Sufficiently detailed analytical simulations early.
  - Detail System level FEM model
  - Highly Detailed mechanism component level model
- Robust Test Plan to validate analysis and design approaches (Validate disturbance requirements)

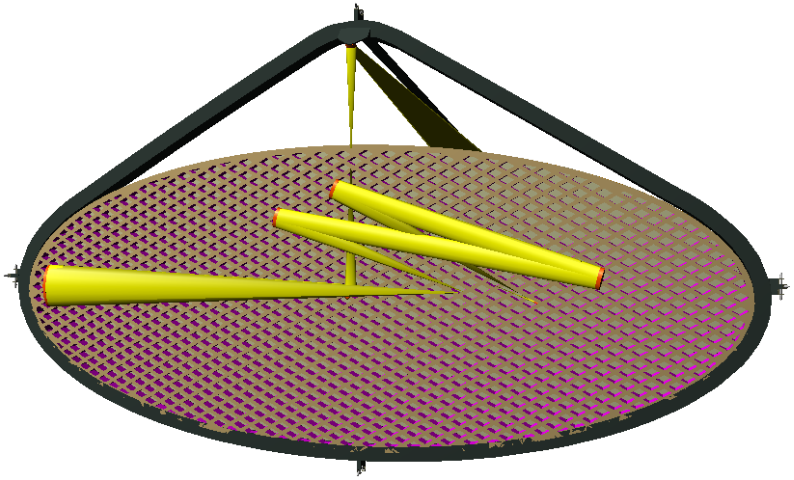
Microdynamics during Observation Sequence - Top Ten Issue

# Overview of the Optical Bench Design



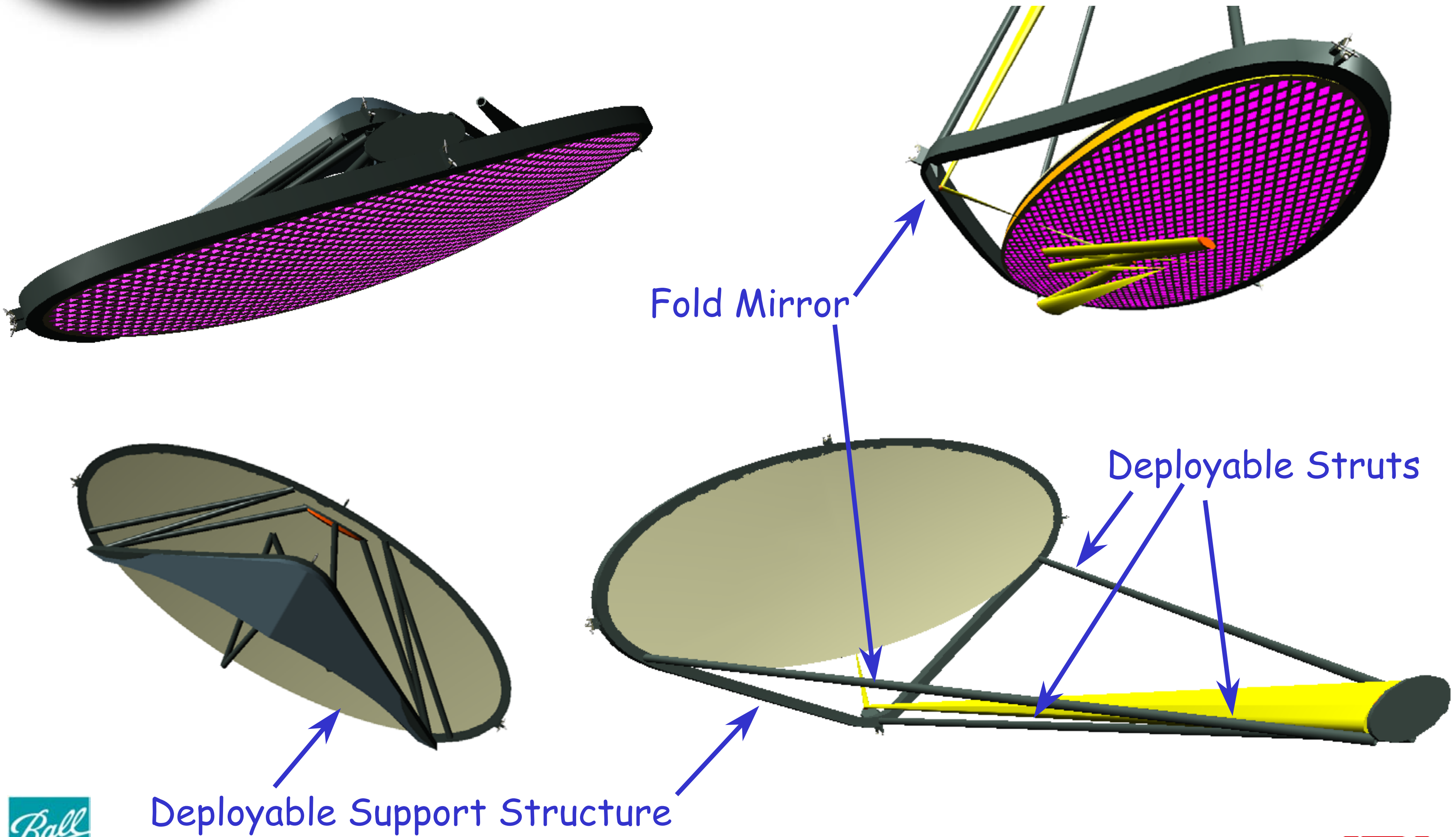
Evolved AMSD Design



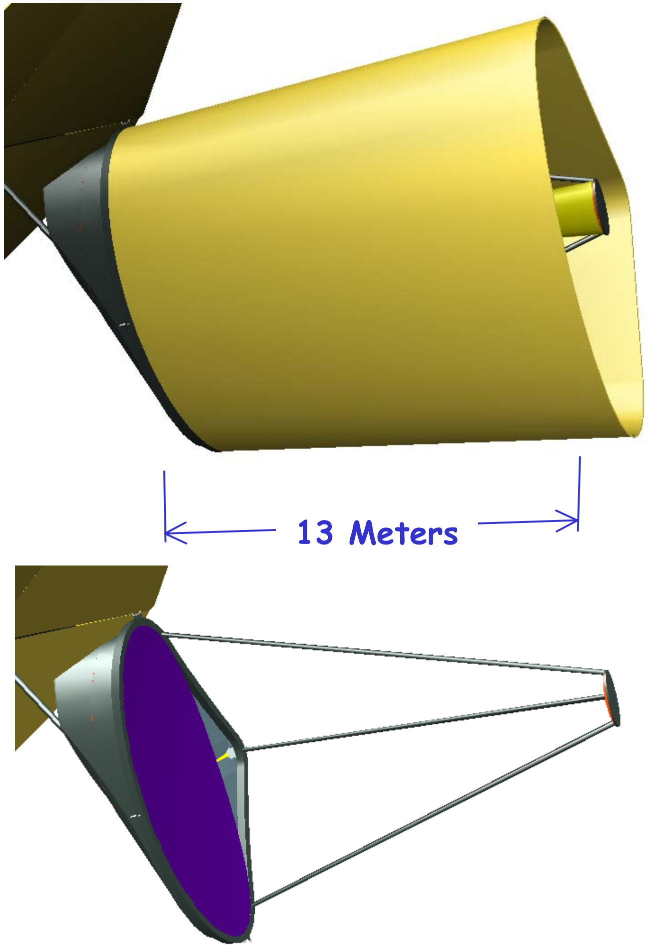


Iso-Grid Graphite Epoxy Bench
- Supports Primary Mirror
- Supports Ancillary Optics
- Supports Science Instruments

# Overview of the Secondary & Fold Mirror Deployment



# Overview of the Baffle Design



Design based on existing Technology Development


AEC-ABLE FASTmast

**Deployable Baffle is evolved approach of NGST Sun Shield Designs**

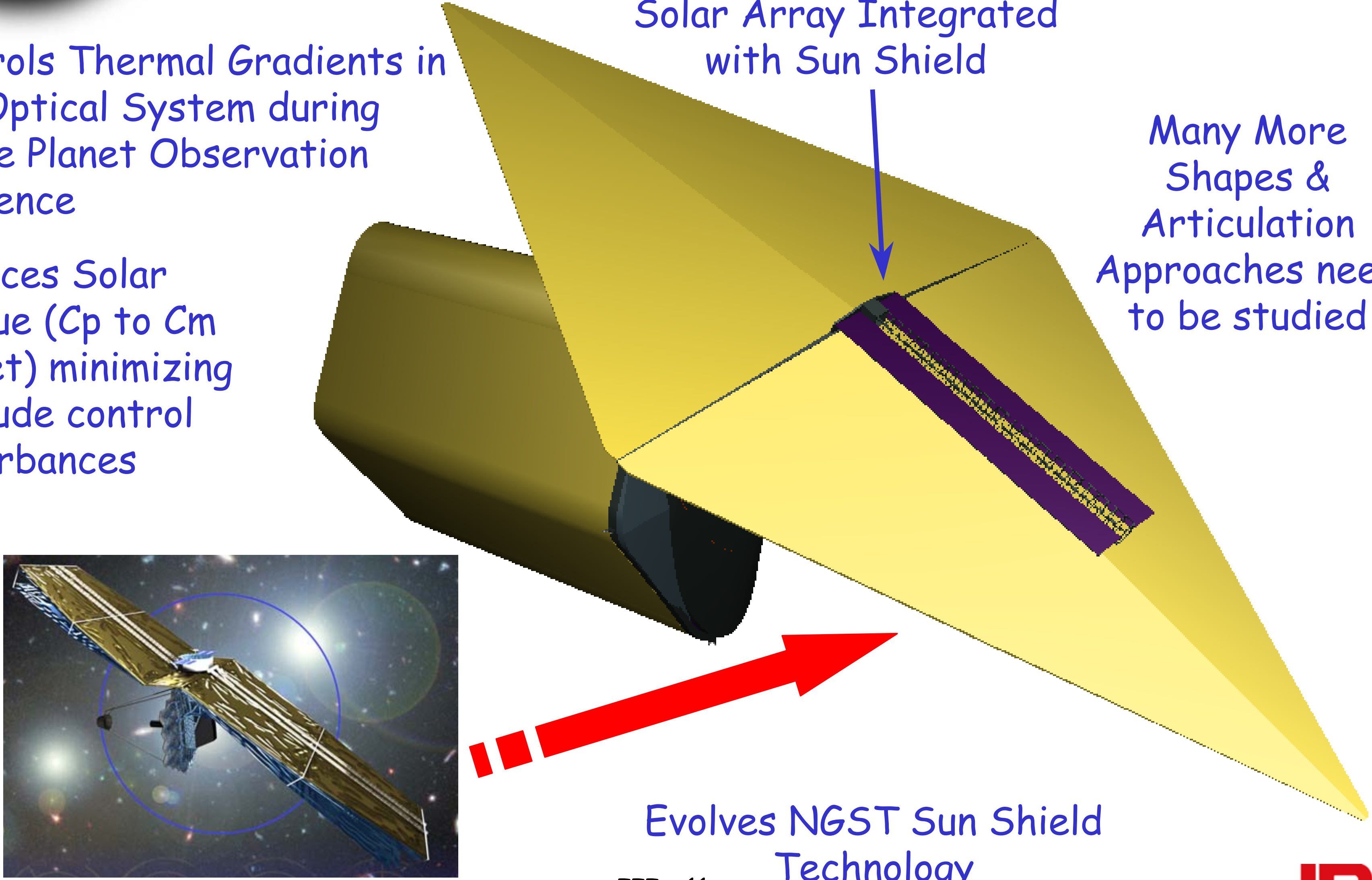
**Continue Trades on Inflatable versus Mechanical Deployment**


ILC Dover Sun Shield

# Overview of the Sun Shield Design

Controls Thermal Gradients in the Optical System during entire Planet Observation Sequence

Balances Solar Torque (Cp to Cm offset) minimizing attitude control disturbances



Solar Array Integrated with Sun Shield

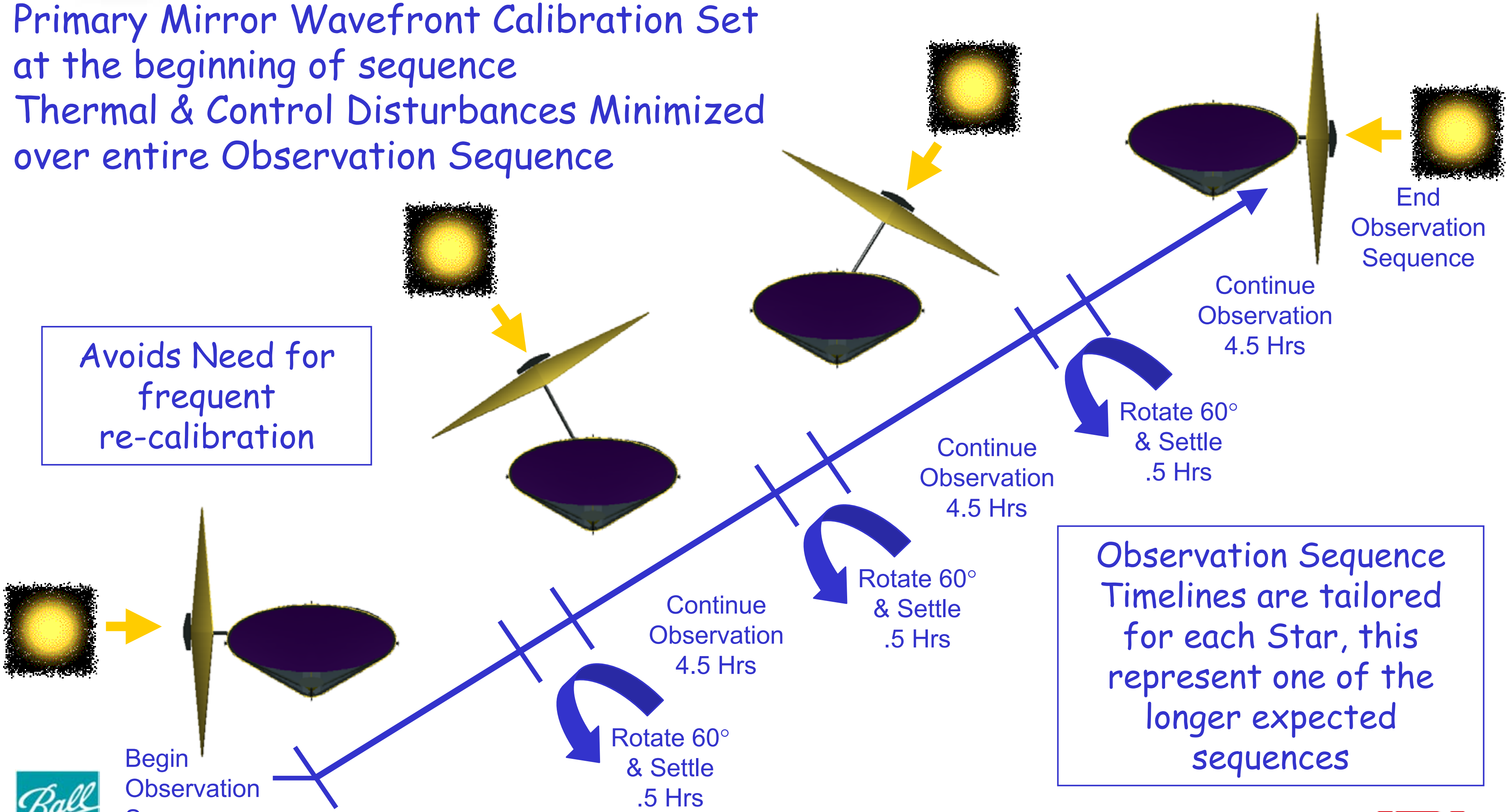
Many More Shapes & Articulation Approaches need to be studied

Evolves NGST Sun Shield Technology

# Articulation of Sun Shield in Planet Search Mode

Primary Mirror Wavefront Calibration Set at the beginning of sequence
Thermal & Control Disturbances Minimized over entire Observation Sequence

Avoids Need for frequent re-calibration



Begin Observation Sequence

Rotate 60° & Settle .5 Hrs

Continue Observation 4.5 Hrs

Rotate 60° & Settle .5 Hrs

Continue Observation 4.5 Hrs

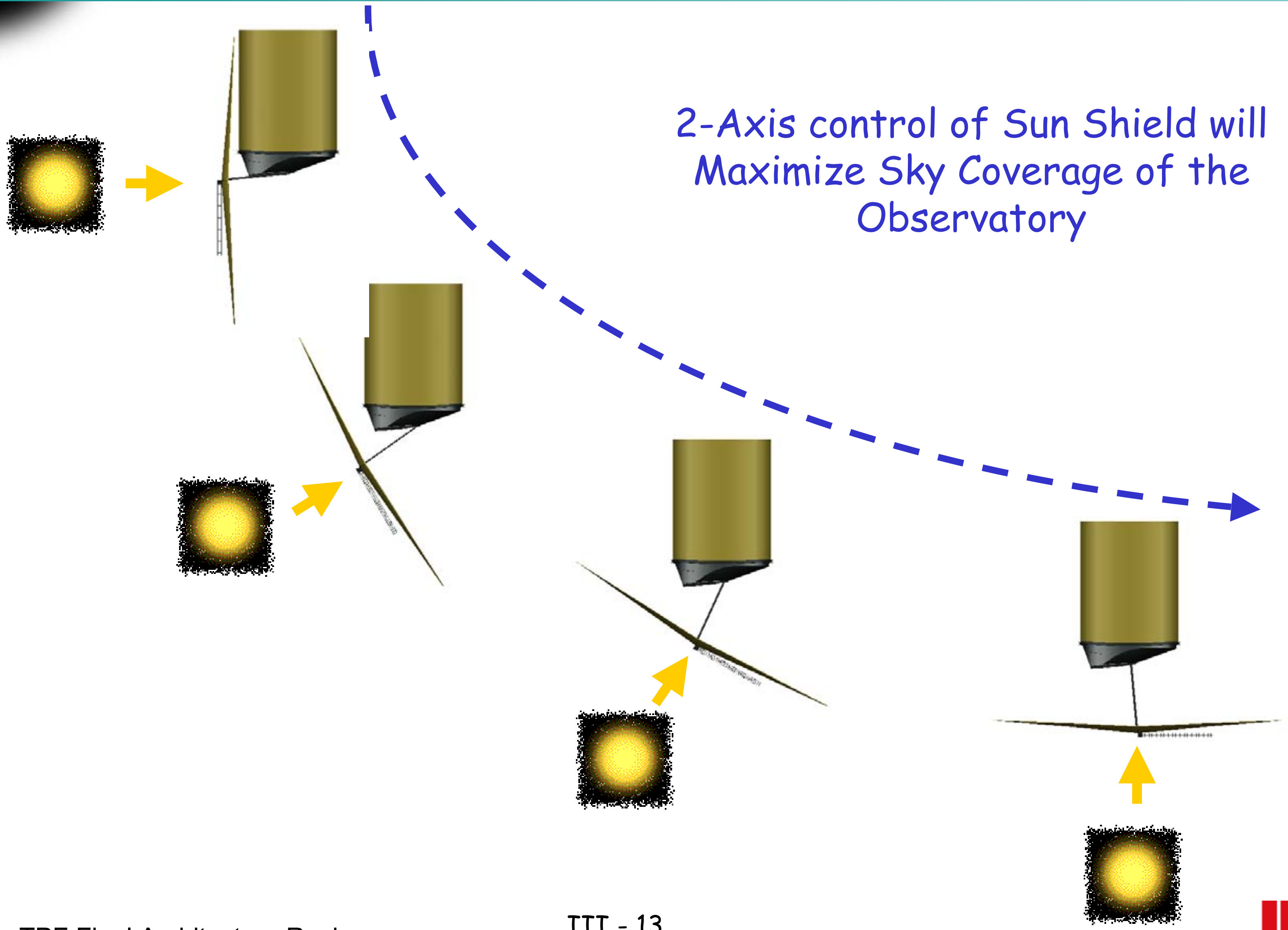
Rotate 60° & Settle .5 Hrs

Continue Observation 4.5 Hrs

End Observation Sequence

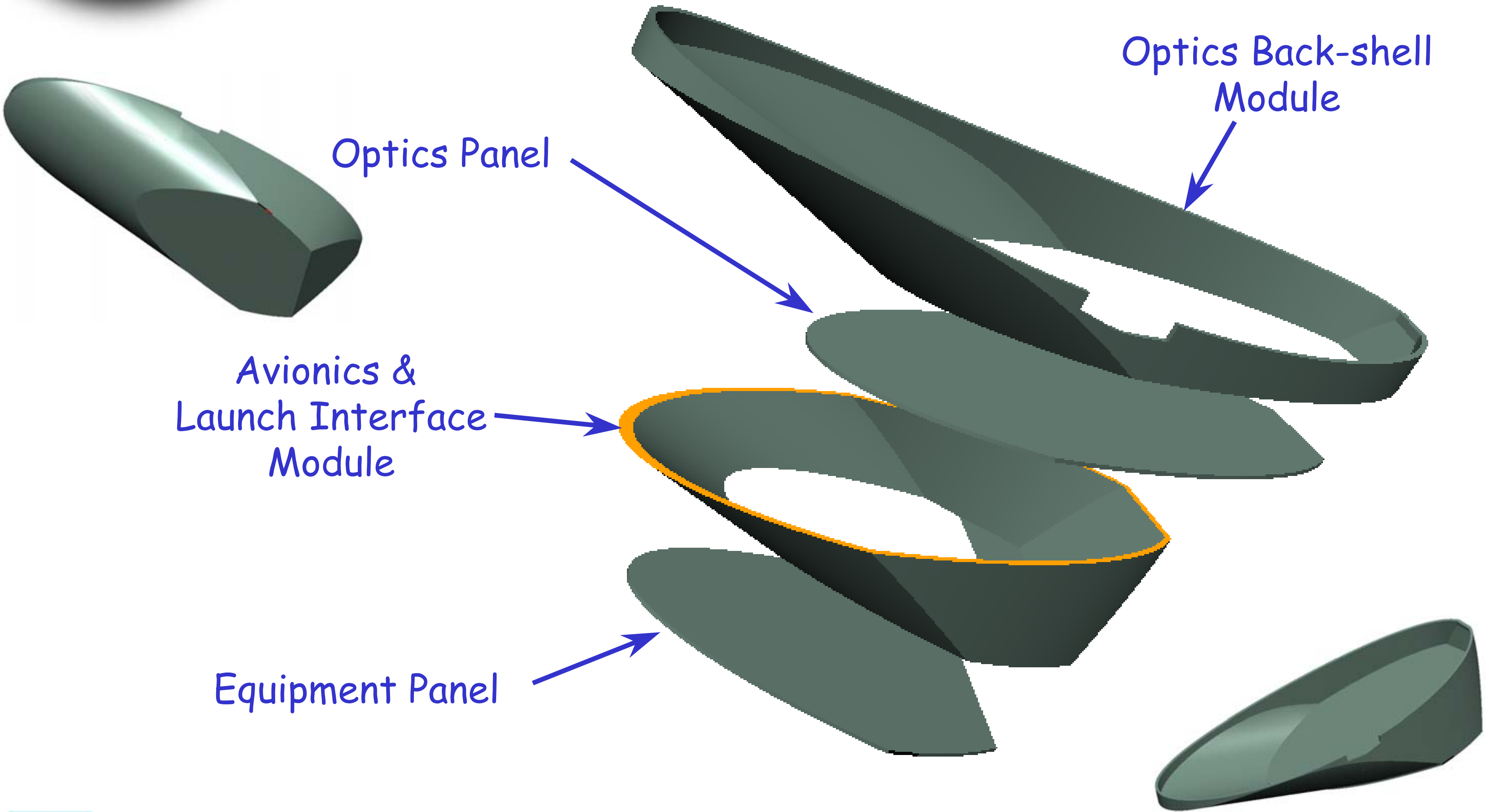
Observation Sequence Timelines are tailored for each Star, this represent one of the longer expected sequences

# Articulation of Sun Shield while Maneuvering to new Stars



2-Axis control of Sun Shield will Maximize Sky Coverage of the Observatory

# Overview of the Asymmetric Bus Design



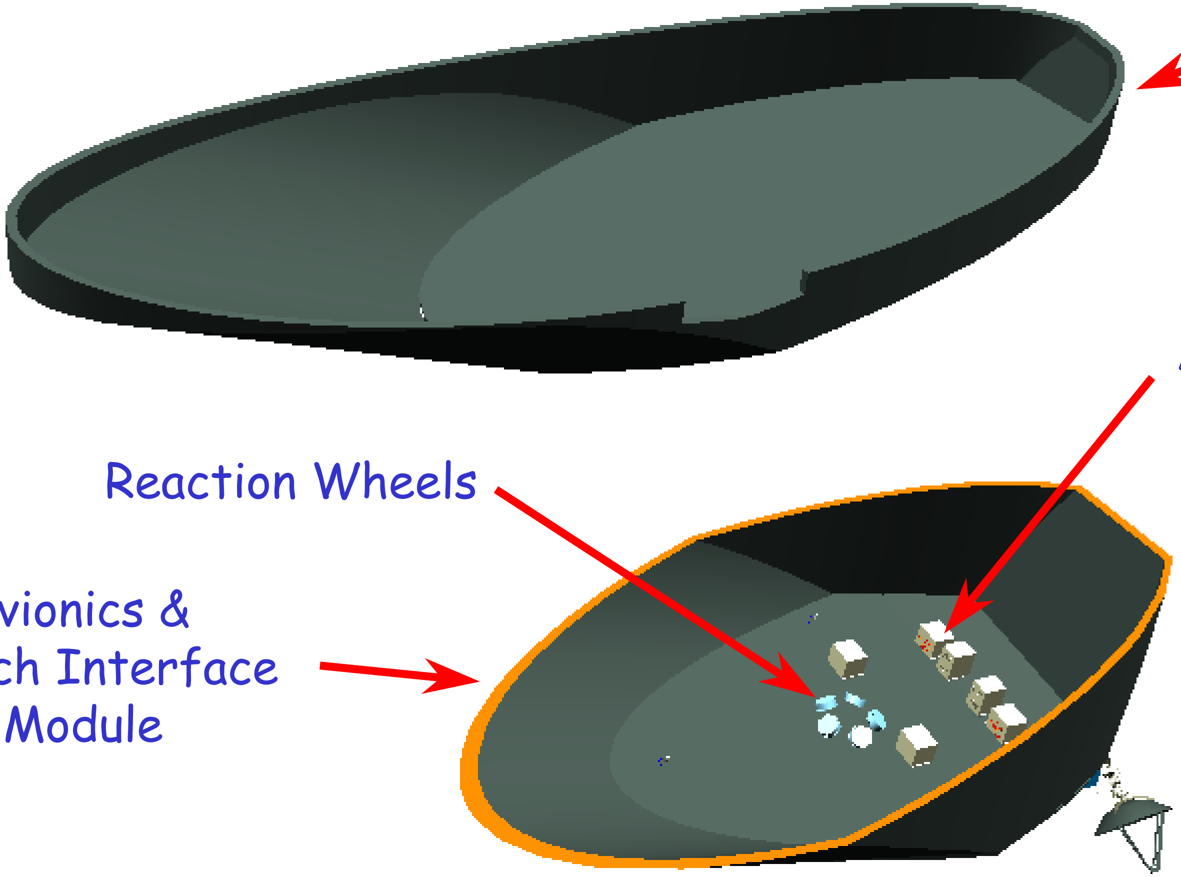
Optics Back-shell Module

Optics Panel

Avionics & Launch Interface Module

Equipment Panel

# Overview of the Modular Composite Assemblies



Optics Back-shell Module

Avionics

Reaction Wheels

Avionics & Launch Interface Module

# The Design Drivers for the TPF Coronagraph Orbit

<u>Primary Design Metrics (Direct Benefits to Science)</u>

- Maximize Sky Coverage
  - Minimize Earth and Moon Interference into Field of View (FOV)
- Minimize Environmental Disturbances
  - Minimize Thermal Variations over an Observation Sequence (~ 24 Hours)
  - Minimize Slew Requirements over an Observation Sequence (~ 24 Hours)
  - Minimize Contamination Influences
- Eliminate or Minimize Station Keeping Requirements (or keep at a frequency of 90 days or less)

<u>Secondary Design Metrics (Direct Benefits to Cost Reduction)</u>

- Minimize Launch Energy
- Maximize Launch Windows
- Minimize Telecommunications Distance
- Maximize Autonomous Servicing Capabilities

# TPF Coronagraph Orbits (Short List)

| Orbit | Advantages | Disadvantages |
|---|---|---|
| L1 or L2 Halo<br>(SOHO & NGST Orbit) | No Eclipse<br>Large Sky Coverage<br>NGST Ground Compatibility<br>NGST Ops Compatibility<br>Low Insertion Energy<br>C3 = -0.69 (km²/s²) | Station Keeping<br>C3 = -0.7 (km²/s²) Direct<br>C3 = -2.2 (km²/s²) Lunar Swingby |
| Arrested Drift Away<br>(Modified Starlight & SIRTF Type Orbit) | ***Minimal Disturbances***<br>No Eclipse<br>Large Sky Coverage<br>No Station Keeping | Moderate Insertion Energy<br>C3 = 0.3 (km²/s²)<br>+<br>220 m/s to arrest drift |
| Distant Geocentric Orbit<br>(Distant Retrograde Orbit) | No Eclipse<br>Sky Coverage (TBD)<br>No Station Keeping<br>Closest to Earth - Autonomous Servicing | Comparable to L2 Insertion<br>C3 = -1.85 (km²/s²)<br>Needs More Optimization |

Trades Need to Continue to Optimize Cost versus Performance

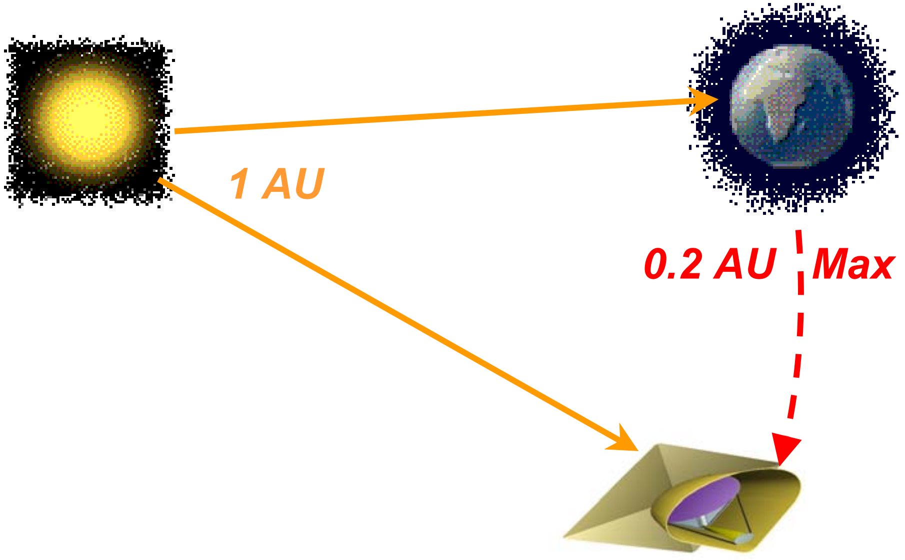
# TPF Coronagraph Orbits (Other Options)

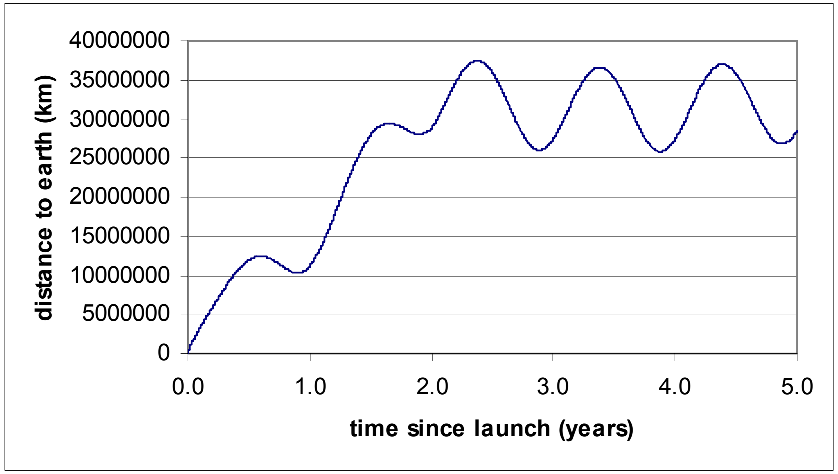
| Orbit | Advantages | Disadvantages |
|---|---|---|
| LEO or GEO | Lowest Insertion Energy<br>Simplest Telecom<br>Autonomous Servicing | Limited Sky Coverage<br>Thermal Snap due to Eclipse<br>Highest Disturbances |
| Standard Drift Away (Starlight & SIRTF Type Orbit) | No Eclipse<br>Large Sky Coverage | Moderate Insertion Energy<br>C3 = 0.3 ($km^2/s^2$)<br>Telecom Requirements |

2nd Tier of Options
Less Attractive for a variety of Reasons

# Overview of the Arrested Drift Away Orbit

- Inject into a Drift away orbit similar to SIM, StarLight, & SIRTF
- Stop the drift at year two, Apply approximately 220 m/s delta-v
- This will circularize the orbit so the distance to the sun will remain very close to 1 AU
- The distance from the spacecraft to earth would not increase without bound
  - Sufficiently far away from the gravitational influence of the earth and moon
  - Earth to spacecraft distance remains near 30 to 35 x $10^6$ km (0.2 AU) for the indefinite future
  - Oscillations between 25 x $10^6$ and 36 x $10^6$ km are due to the spacecraft orbit being not in the ecliptic plane
- Spacecraft then is in an earth-trailing orbit
- Ground contacts near 6 PM (local) every day





# Overview of the L2 Halo Orbit

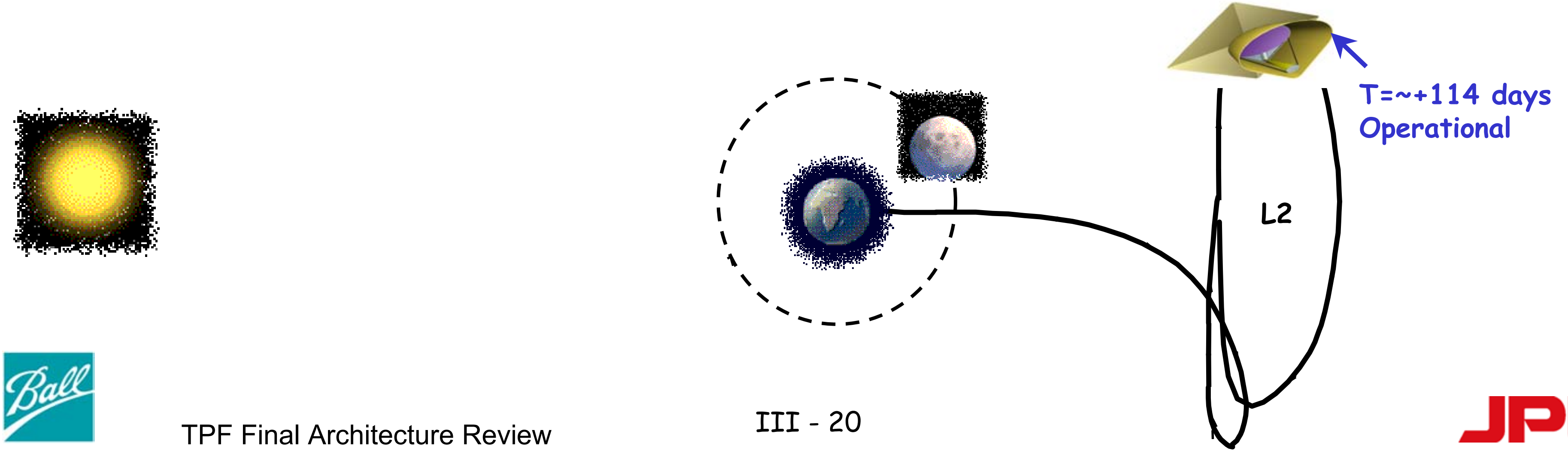
Inject into a L2 Halo orbit similar to MAP & NGST, the L2 Sun-Earth Lagrange point is 1.5 million km from Earth.

The L2 point is unstable on a time scale of approximately 23 days, which requires satellites parked at these positions to undergo regular course and attitude corrections

Direct Insertion C3 = -0.7 (km$^2$/s$^2$) or via Lunar Flyby C3 = -2.2 (km$^2$/s$^2$) (3-5 lunar phasing loops, then a ~100 day cruise to L2)

Minimizes environmental disturbances and maximize observing efficiency

L2 provides for a very stable thermal environment and near 100% observing efficiency since the Sun, Earth, and Moon are always behind the instrument's field of view.



# Overview of the Distant Geocentric Orbit (Results are preliminary)

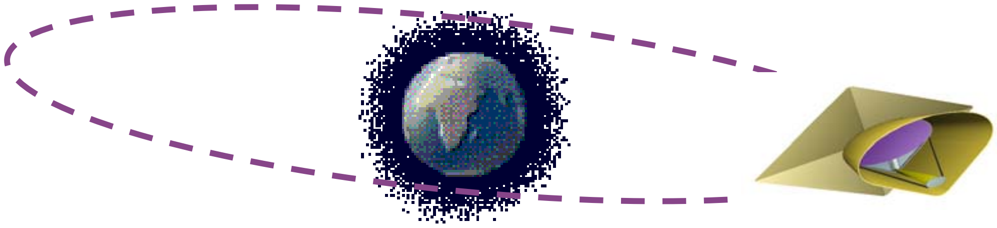
Reasonably far from the Earth
  - No eclipse
  - No thermal snap

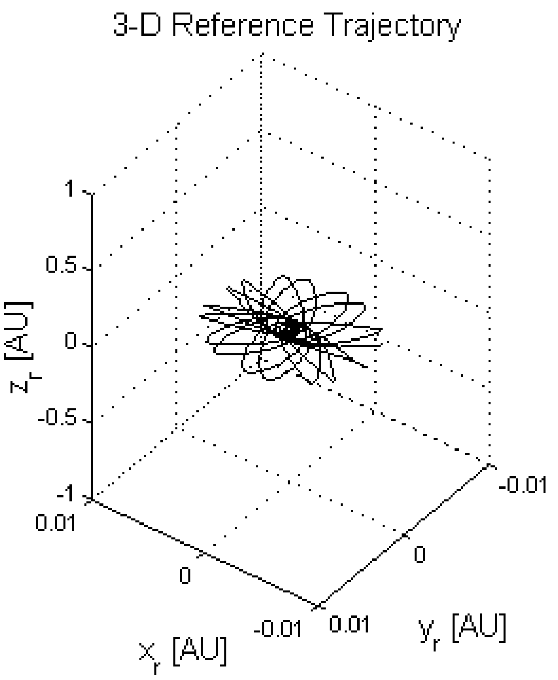
Reasonable Telecom Distance (~.2 AU)

Stable Orbit that avoid the Lagrange point orbits no stationkeeping

$C3 = -1.85\ km^2/sec^2$

Appealing Orbit which warrants further study





3-D Reference Trajectory

# Overview of the TPF Coronagraph Launch Segment

## Design Drivers

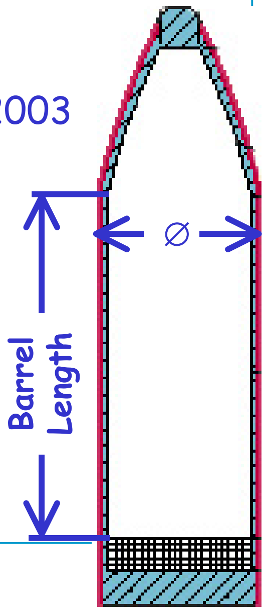
- Large Monolithic Mirror ( 4 x 10 Meters)
- ~ 6,000 kg Observatory Launch Mass
- Required Escape Capability of C3 > 0.3 $km^2/sec^2$

## Potential Launchers

- Ariane 5 (AR5E) - Evolved Version of AR5G
  7,250 kg for C3 of 0.3 $km^2/sec^2$
- Atlas V 551 - 1st Flight 2002
  6,300 kg for C3 of 0.3 $km^2/sec^2$
- Delta IV (4050-H19) - 1st Flight 2003
  9,255 kg for C3 of 0.3 $km^2/sec^2$

## Launcher Fairings

| Launcher | ∅ | Barrel Length (M) |
|---|---|---|
| Ariane | 5 | 10 |
| Atlas | 5 | 7 (Too Short) |
| Delta | 5 | 11 |



# TPF Coronagraph Launch Segment


Boeing Delta IV Heavy

Major Features

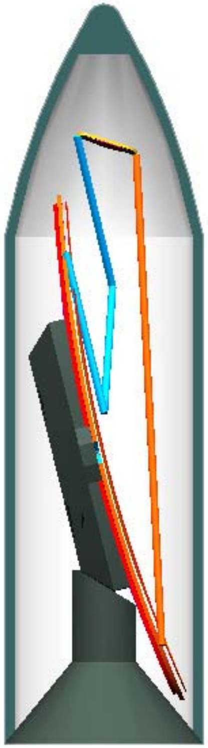
- Fully Compatible with Delta IV Heavy
  - Delta IV 1st Flight 2002
  - Delta IV Heavy 1st Flight 2003
- Room For Larger Observatories
  - Layouts of Mirrors up to 4 x 13 Meters
- Robust Launch Margins
  - Launch Mass ~6,000 kg
  - Launch Capability of 9,255 kg to C3 = 0.3 $km^2/sec^2$
  - Launch Margin of 35%
- Direct Injection to Heliocentric Earth Trailing Drift Away Orbit

# Delta IV (4050-H19) Heavy Launch Configuration

**Baseline 4 x 10 Primary Mirror**

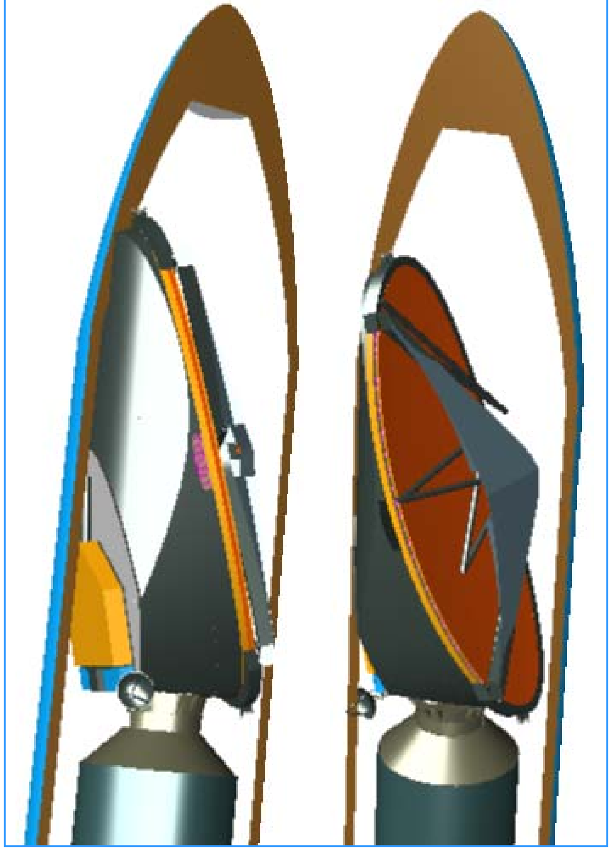
- Several Packaging Approaches still need to be explored
- Currently not taking full advantage of Delta IV capabilities (35% Launch Margin)
- Need to work trades to maximize primary mirror with adequate launch margin (20 to 25% pre phase A margins should be acceptable)

**Alternative 4 x 13 Primary Mirror**



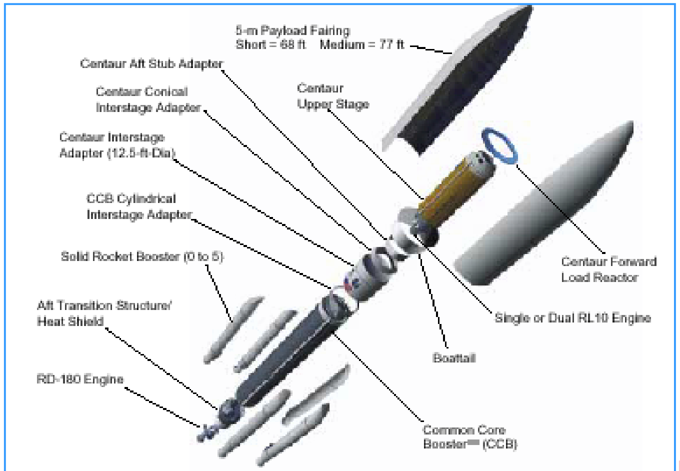
# Atlas V 551 Launch Configuration (Alternative)

## Baseline 4 x 10 Primary Mirror

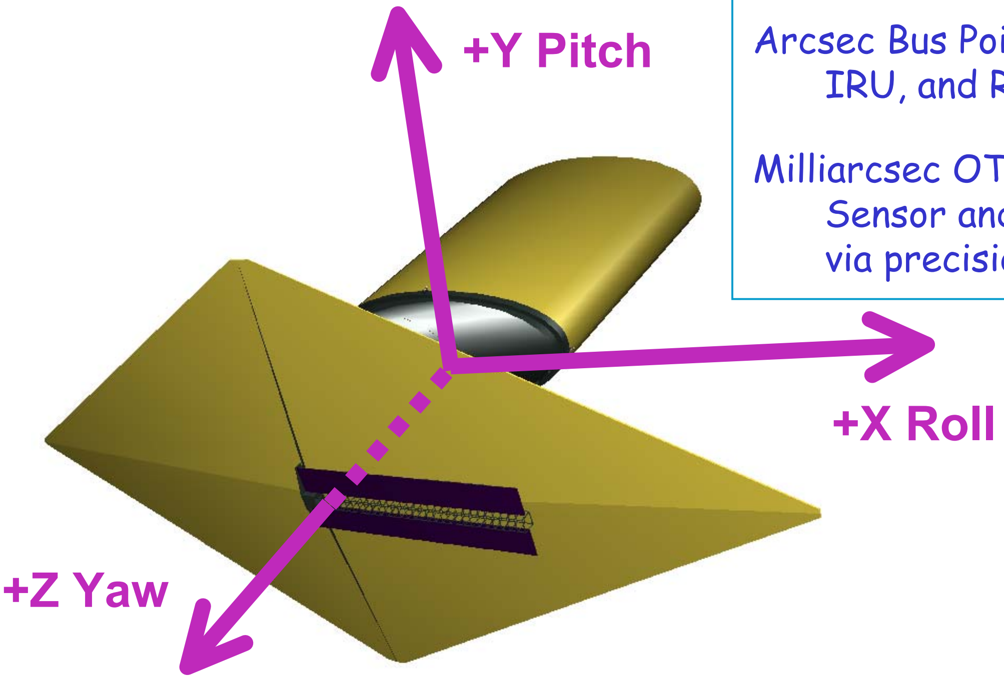


- Atlas V 1st Flight 2002
- *Not* Compatible with Standard Atlas V 551
  - Largest Fairing Inadequate (Need Slightly longer Fairing)
  - Add 1 Meter in length to barrel section
  - Relatively Straight forward Modification
  - *However* it will Reduce Performance
- Minimal Launch Margins
  - Launch Mass ~6,000 kg
  - Launch Capability of 6,300 kg to C3 = 0.3 $km^2/sec^2$
  - Launch Margin of 5%
- Direct Injection to Earth Trailing Drift Away Orbit

Need to work trades to reduce primary mirror with adequate launch margin (20 to 25% pre phase A margins should be acceptable)



# Summary of The Attitude Determination & Control (ADCS) Subsystem



Pointing Control Architecture has been partially validated with preliminary End-to-End modeling

Arcsec Bus Pointing Accuracy via precision Star Trackers, IRU, and RWA's (Existing Technology)

Milliarcsec OTA LOS Jitter/Stability via Fine Guidance Sensor and Fine Steering Mirror (FSM) with FSM Tip/Tilt via precision body pointing

<u>Key ADCS Requirements for the TPF Coronagraph</u>

| | |
|---|---|
| Instrument LOS Pointing Stability: | 1 milliarcsecond (1$\sigma$, per axis) |
| Spacecraft Bus Attitude Control: | 1 arc second (1$\sigma$, cross-axes) |
| Spacecraft Bus Attitude Knowledge: | 4 arc seconds (1$\sigma$, cross-axes) |

# LOS Pointing and Attitude Control Requirements Derived From Image Quality Requirements

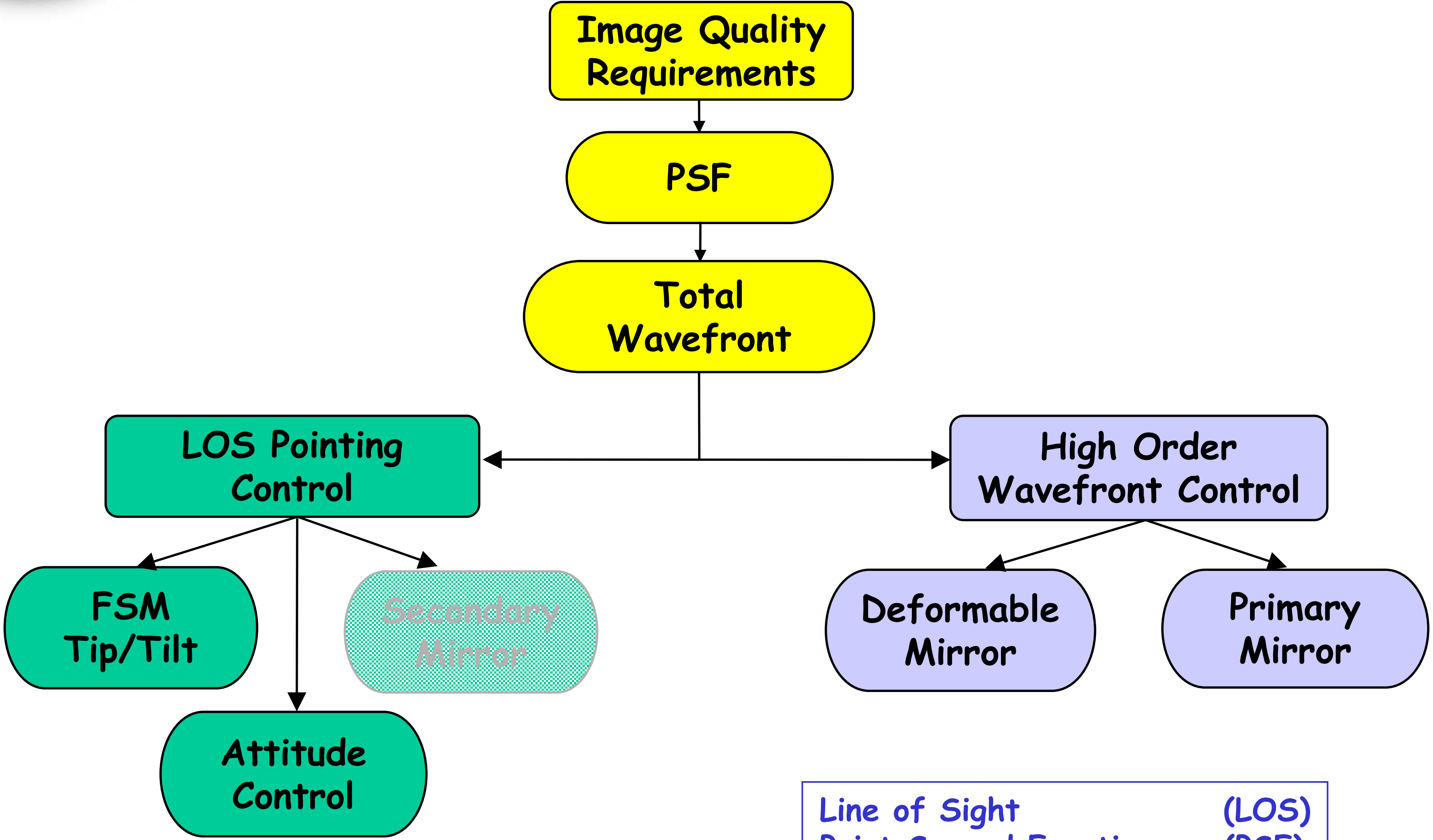


Image Quality Requirements

PSF

Total Wavefront

LOS Pointing Control

High Order Wavefront Control

FSM Tip/Tilt

Secondary Mirror

Attitude Control

Deformable Mirror

Primary Mirror

| | |
|---|---|
| Line of Sight | (LOS) |
| Point Spread Function | (PSF) |

# Key Pointing Requirements Driven By LOS Stability & Guide Star Acquisition

Instrument LOS Pointing Stability: 1 mas (1$\sigma$, per axis)

- Allocated from wavefront error budget
- Spectral content up to 100 Hz (TBR)

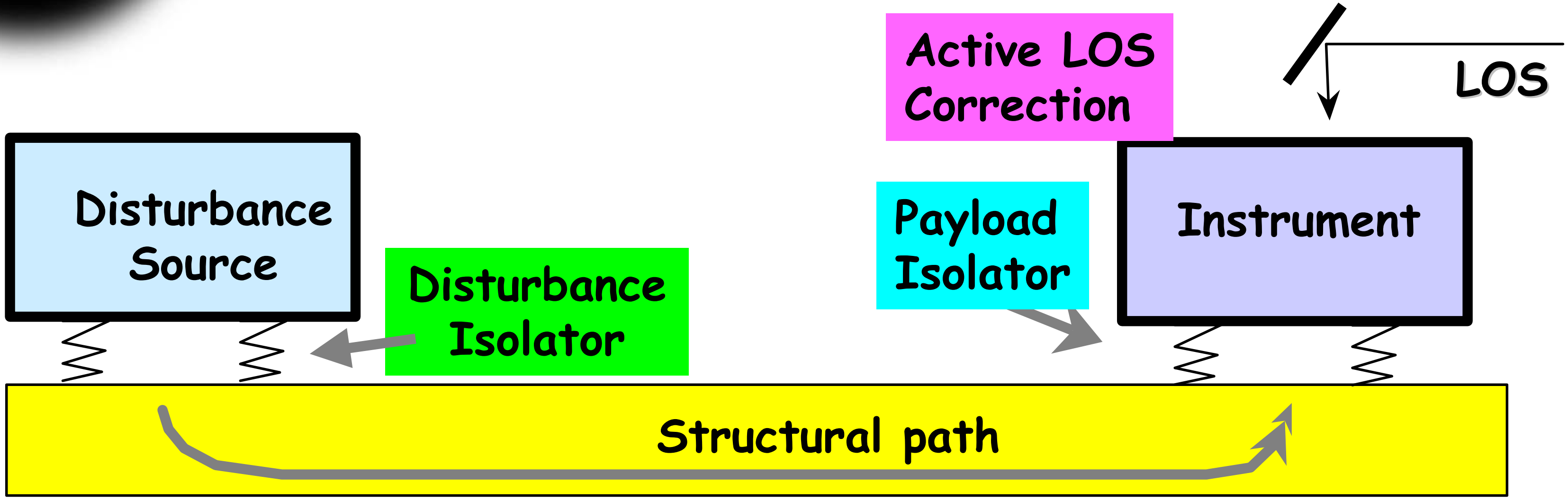
Spacecraft Bus Attitude Control: 10 mas (1$\sigma$, cross-axes)

- Minimize FSM tip/tilt to satisfy wavefront & beam shear requirements
- Using Fine Guidance Sensor (FGS) and Reaction Wheel Assembly (RWA) control

Spacecraft Bus Attitude Knowledge: 4 arc seconds (1$\sigma$, cross-axes)

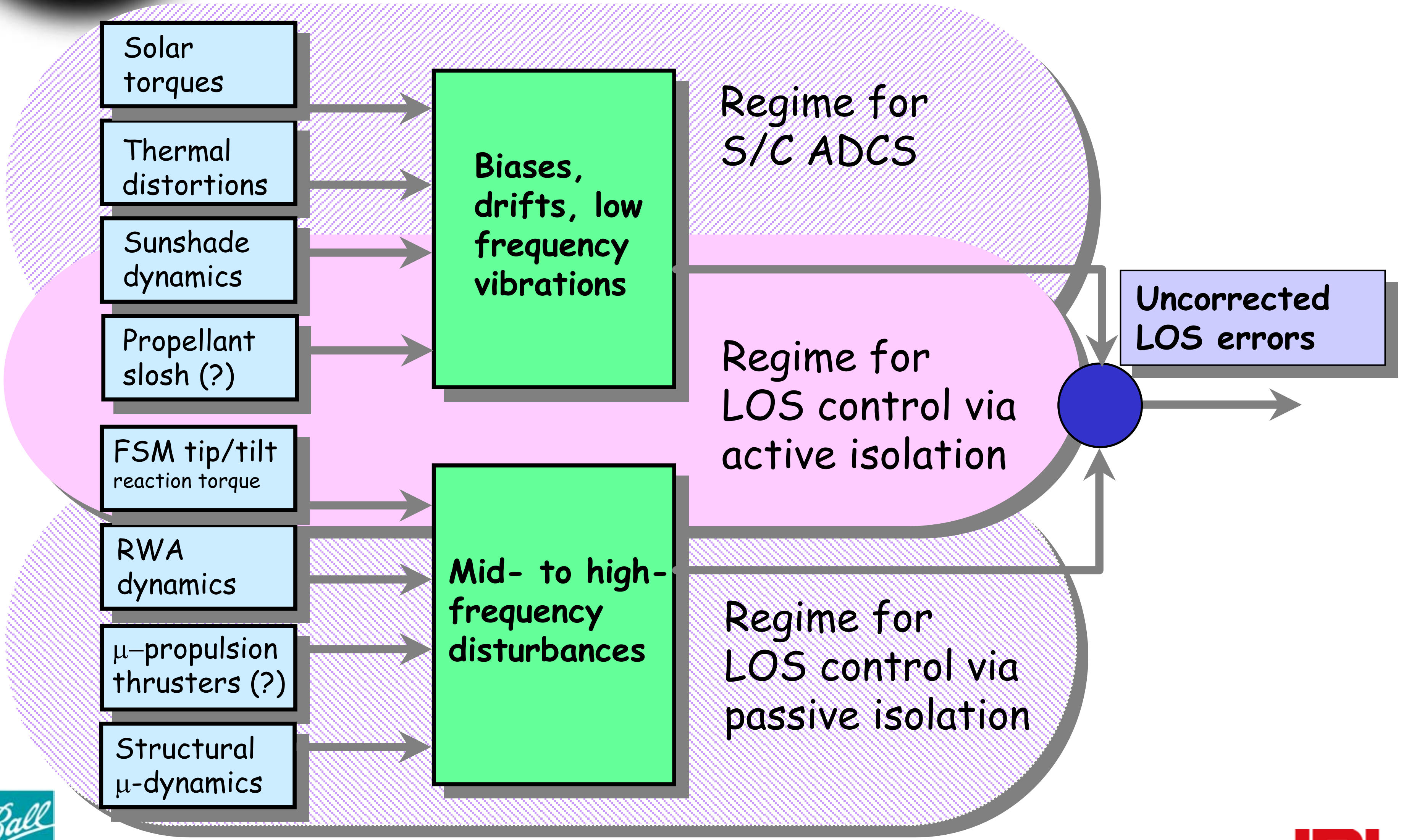
- Fine guidance system acquisition (place guide star in FGS FOV)
- Using spacecraft bus stellar-inertial system

# Several Approaches Available For Stabilizing LOS Motion



- Five opportunities exist to control high frequency disturbances
  - Reduce disturbance source levels with better equipment
  - Isolate the disturbance source
  - Form structural isolation links between systems
  - Isolate instrument(s) from disturbance
  - Reject LOS motion with tip/tilt mirror

# LOS Pointing Control Approach Tailored to Disturbance Spectral Content



Solar torques

Thermal distortions

Sunshade dynamics

Propellant slosh (?)

FSM tip/tilt reaction torque

RWA dynamics

μ–propulsion thrusters (?)

Structural μ-dynamics

**Biases, drifts, low frequency vibrations**

**Mid- to high-frequency disturbances**

Regime for S/C ADCS

Regime for LOS control via active isolation

Regime for LOS control via passive isolation

**Uncorrected LOS errors**

# Tiered ADCS Design Approach Mitigates Disturbances During Science Observations

| Disturbance Source | Mitigating Factors Available |
|---|---|
| RWA Vibration<br>(e.g., static & dynamic imbalance) | • Precision spin balance<br>• Isolation systems (passive or active)<br>• Benign RWA spin rate range selected (minimize c.p.-c.m. offset)<br>• Structural design minimizing mechanical vibration transmission<br>• Micro-propulsion technology (e.g., FEEP, mPPT) |
| Structural dynamic motion<br>(e.g., flexible sun shield) | • Smooth, profiled re-targeting maneuvers minimize settling time<br>• Low bandwidth bus controller<br>• Active isolation system (e.g., fine steering mirror)<br>• Passive damping enhancement (e.g., visco-elastic coatings) |
| Secular torque accumulation<br>(e.g., solar radiation pressure) | • Pre-position articulated sun shield to minimize c.p.-c.m. offset<br>• FSM counter-steers to maintain LOS pointing |
| Thermal distortion | • Sun shield provides thermal stability<br>• FSM counter-steers to maintain LOS pointing |
| Propellant slosh | • Smooth, profiled re-targeting maneuvers minimize settling time<br>• Low bandwidth bus controller<br>• Multiple, small, baffled tanks<br>• Non-liquid propellant (Xenon, Teflon, Nitrogen) |
| Thruster impulse | • No pulsing (of conventional thrusters) during science observations |
| Structural micro-dynamics | • Thermally stable design<br>• Structural design minimizing mechanical vibration transmission |

# LOS Control Trades Central to Iterative System Design Approach

| Design Trade | Issues |
|---|---|
| **LOS Pointing Control Architecture** | |
| • S/C body pointing w/o FSM<br>vs.<br>• FSM & S/C control off-load | • FSM tip/tilt introduce wavefront & beam shear errors<br>• FSM provides active isolation to mitigate LOS jitter |
| **Fine Guidance Sensor Options** | |
| • CCD<br>vs.<br>• Quad cell | • Read-out rate to support FSM control bandwidth |
| • Sensor FOV | • FGS acquisition given S/C attitude knowledge capability |

Instrument LOS Pointing Stability: 1 mas (1$\sigma$, per axis)

# Spacecraft Attitude Sensor Trades Part of Iterative System Design Approach

**Attitude Sensor Options**

| Design Trade | Issues |
|---|---|
| - Star tracker (ST)<br>vs.<br>- Star tracker & IRU | - Accuracy for Fine Guidance System (FGS) acquisition (fine guidance sensor FOV)<br>- Cost of sensor suite |
| - ST alignment & placement | - ST parallel to instrument LOS simplifies FGS acquisition<br>- Integration complexity |
| - ST redundancy (3 vs. 2) | - Attitude knowledge requirements about each axis |

Spacecraft Bus Attitude Knowledge: 4 arc seconds ($1\sigma$, cross-axes)

# Attitude Control Trades Part of Iterative System Design Approach

| Design Trade | Issues |
|---|---|
| **Bus Actuator Options** | |
| • RWA | • Induced vibration (IV) at instrument LOS |
| vs. | |
| • RWA & μ-propulsion | • IV, mass, power, optics contamination, cost |
| • RWA sizing & quantity | • Agility (slew & settle time reducing science observation time)<br>• Angular momentum storage during observations (c.m.-c.p. offset due to sun shield design)<br>• IV from more small wheels or fewer large wheels |
| **Controller Bandwidth** | |
| • Low-bandwidth<br>vs.<br>• High-bandwidth | • Control-structure interaction w/ sun shield & propellant slosh<br>• Noise transmission, disturbance rejection, response time<br>• Complexity of ADCS control algorithms<br>• FSM tip/tilt dynamic range & beam shear sensitivity |

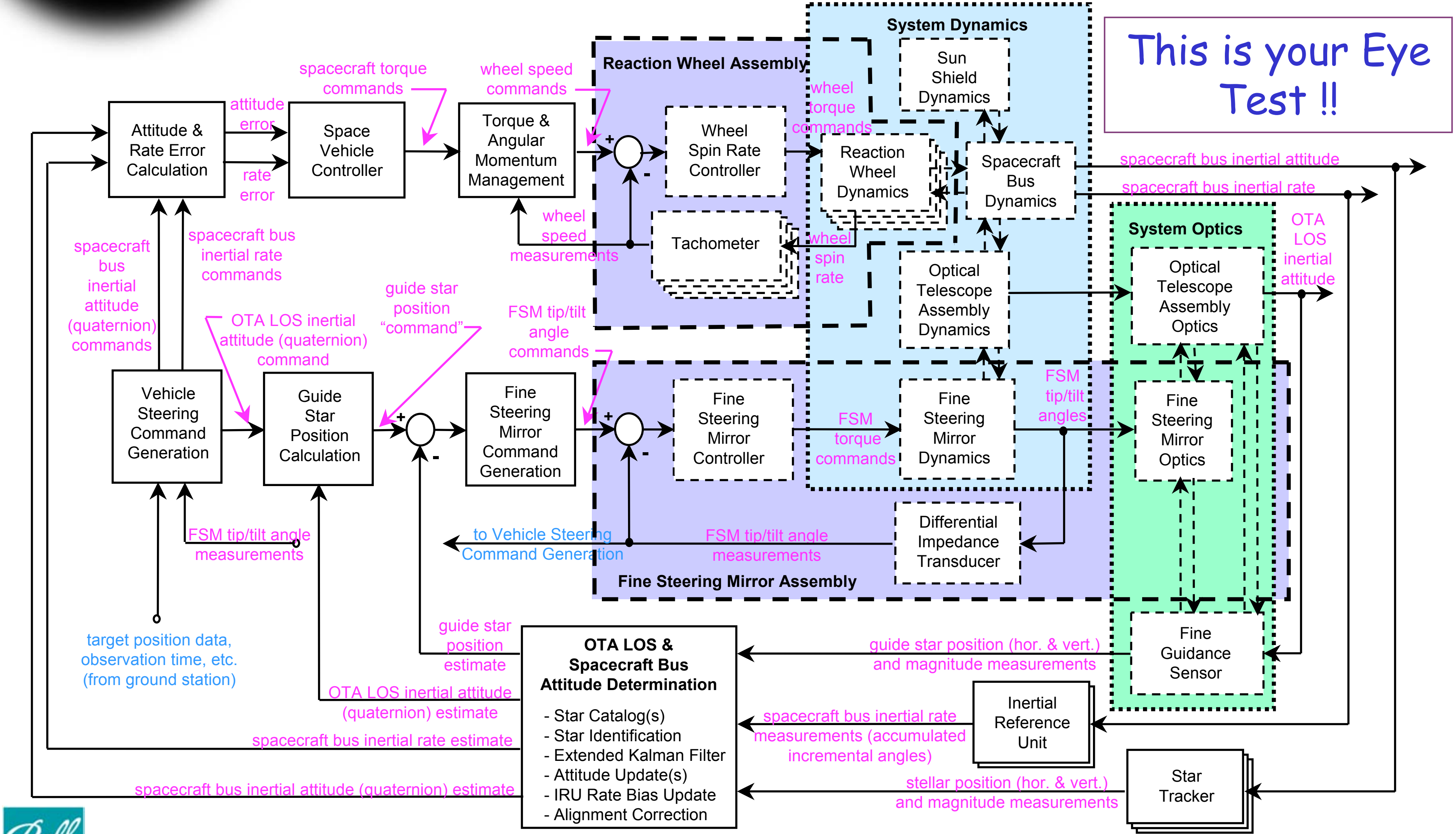
Spacecraft Bus Attitude Control: 10 mas ($1\sigma$, cross-axes)

# Vibration Isolation Trades Part of Iterative System Design Approach

| Design Trade | Issues |
|---|---|
| **Vibration Isolator Design** | |
| • Passive<br>•Active<br>• Passive & active elements | • Effectiveness of passive isolation at lower frequencies<br>• Complexity of active isolation<br>• Benefits & risk reduction of having both |
| • Isolate disturbance sources<br>• Isolate payload<br>• Isolate both | • Complexity/feasibility of isolating instrument<br>• Relative simplicity of isolating RWA array<br>• Other disturbance sources include sun shield and propellant slosh |
| **RWA Spin Balance** | |
| • High precision<br>• Moderate<br>• None | • Cost of high precision balance process<br>• Single point failure if wheel noise increases<br>• Acceptability of lower level spin balance |

# Integrated ADCS & Instrument Control Provides Precision LOS Pointing & Stability

This is your Eye Test !!



Attitude & Rate Error Calculation

attitude error

rate error

Space Vehicle Controller

spacecraft torque commands

Torque & Angular Momentum Management

wheel speed commands

wheel speed measurements

**Reaction Wheel Assembly**

Wheel Spin Rate Controller

Tachometer

wheel torque commands

wheel spin rate

**System Dynamics**

Sun Shield Dynamics

Reaction Wheel Dynamics

Spacecraft Bus Dynamics

Optical Telescope Assembly Dynamics

Fine Steering Mirror Dynamics

spacecraft bus inertial attitude

spacecraft bus inertial rate

**System Optics**

Optical Telescope Assembly Optics

OTA LOS inertial attitude

Fine Steering Mirror Optics

Fine Guidance Sensor

spacecraft bus inertial attitude (quaternion) commands

spacecraft bus inertial rate commands

Vehicle Steering Command Generation

OTA LOS inertial attitude (quaternion) command

Guide Star Position Calculation

guide star position "command"

Fine Steering Mirror Command Generation

FSM tip/tilt angle commands

Fine Steering Mirror Controller

FSM torque commands

FSM tip/tilt angles

Differential Impedance Transducer

FSM tip/tilt angle measurements

to Vehicle Steering Command Generation

**Fine Steering Mirror Assembly**

FSM tip/tilt angle measurements

target position data, observation time, etc. (from ground station)

guide star position estimate

OTA LOS inertial attitude (quaternion) estimate

spacecraft bus inertial rate estimate

spacecraft bus inertial attitude (quaternion) estimate

**OTA LOS & Spacecraft Bus Attitude Determination**

- Star Catalog(s)
- Star Identification
- Extended Kalman Filter
- Attitude Update(s)
- IRU Rate Bias Update
- Alignment Correction

guide star position (hor. & vert.) and magnitude measurements

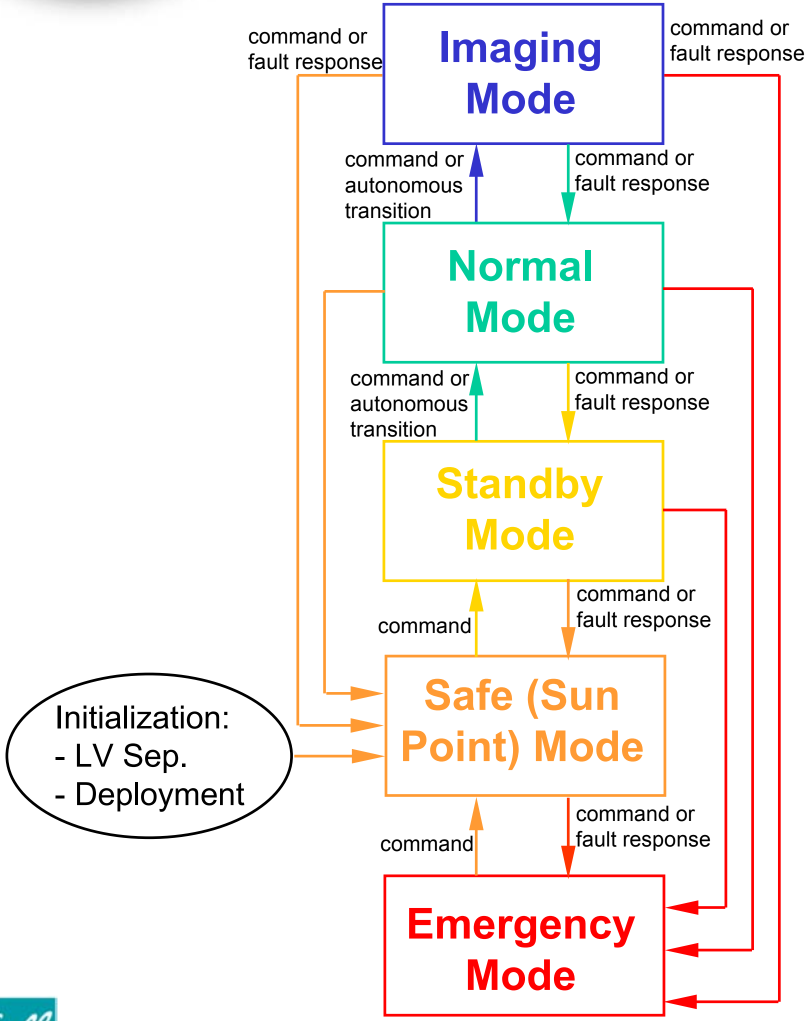
spacecraft bus inertial rate measurements (accumulated incremental angles)

Inertial Reference Unit

stellar position (hor. & vert.) and magnitude measurements

Star Tracker

# *Operational Mode Architecture Emphasizes Systematic Transition Into Science Imaging With Fault Detection & Space Vehicle Safing Paths*



**Imaging (Precision Point) Mode:**
- Fine guidance sensor provides measurements for FSM-controlled LOS pointing
- Spacecraft bus controlled to minimize FSM tip/tilt angles using RWA array in narrow spin speed range

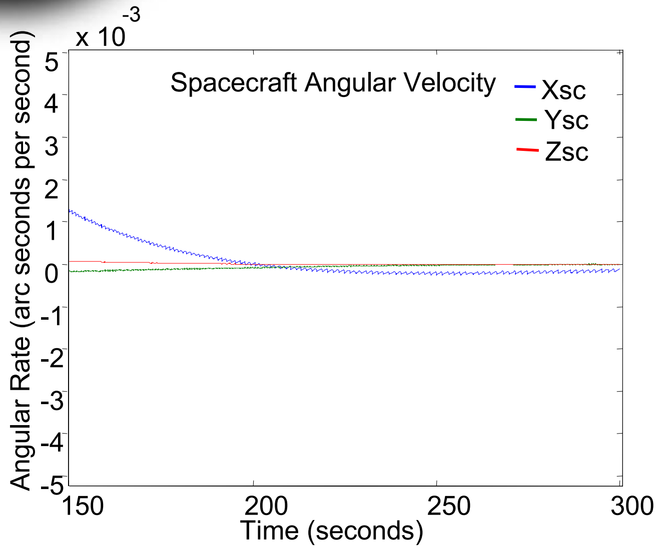
**Normal (Point) Mode:**
- Control vehicle to commanded inertial attitude using RWA array for slew and settle maneuvers
- Sun shield articulated to desired orientation
- Manage angular momentum with thrusters
- Stellar-inertial attitude determination

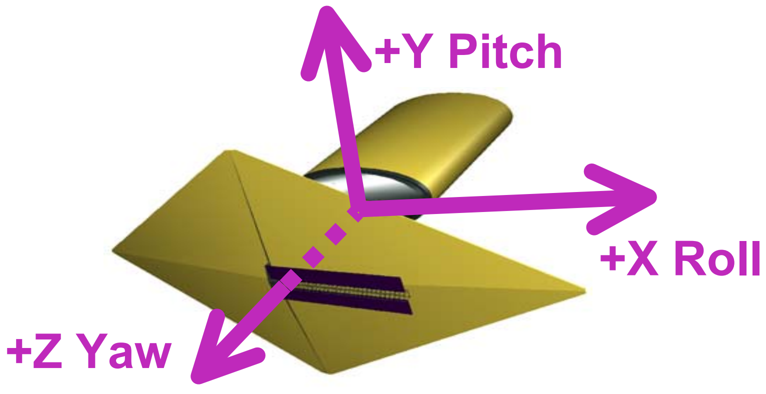
**Standby Mode:**
- Control vehicle in commanded attitude using RWA array
- Manage angular momentum with thrusters and articulated sun shield
- Stellar-inertial attitude determination

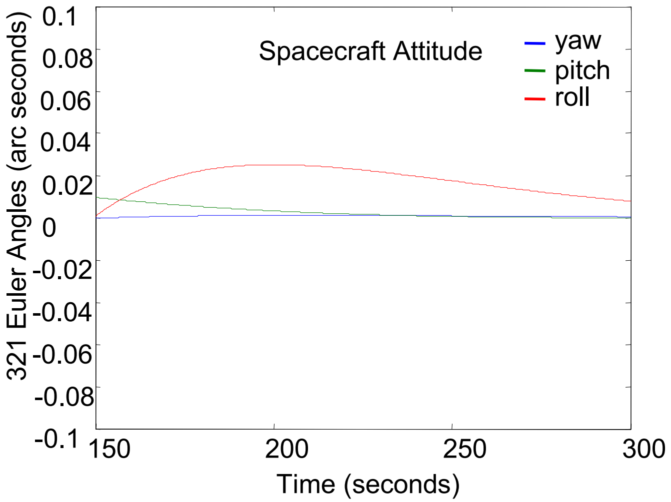
**Safe (Sun Point) Mode:**
- Point solar panels at sun using RWA array
- Manage angular momentum with thrusters
- Sun shield placed in nominal orientation
- Attitude determination via coarse sun sensors

**Emergency Mode:**
- Robust, power-positive, low- (or zero-) fuel consumption mode
- Attitude knowledge from coarse sun sensors sensors
- Does not require on-board processor

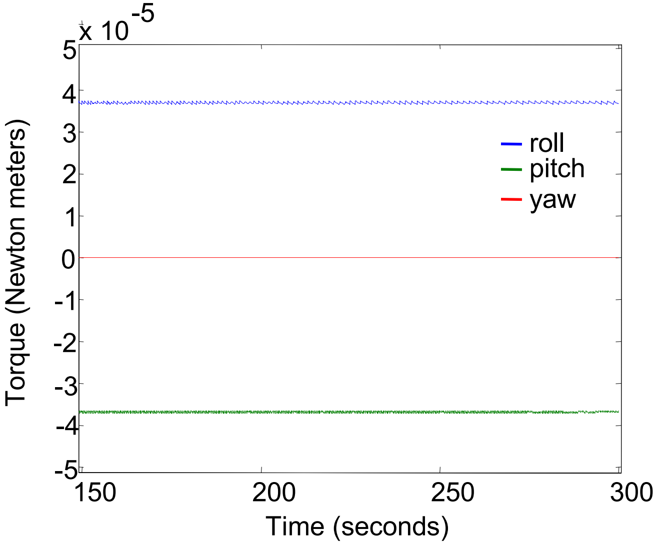
# Sample Simulation Results: RWA Control of Solar Torque Disturbance



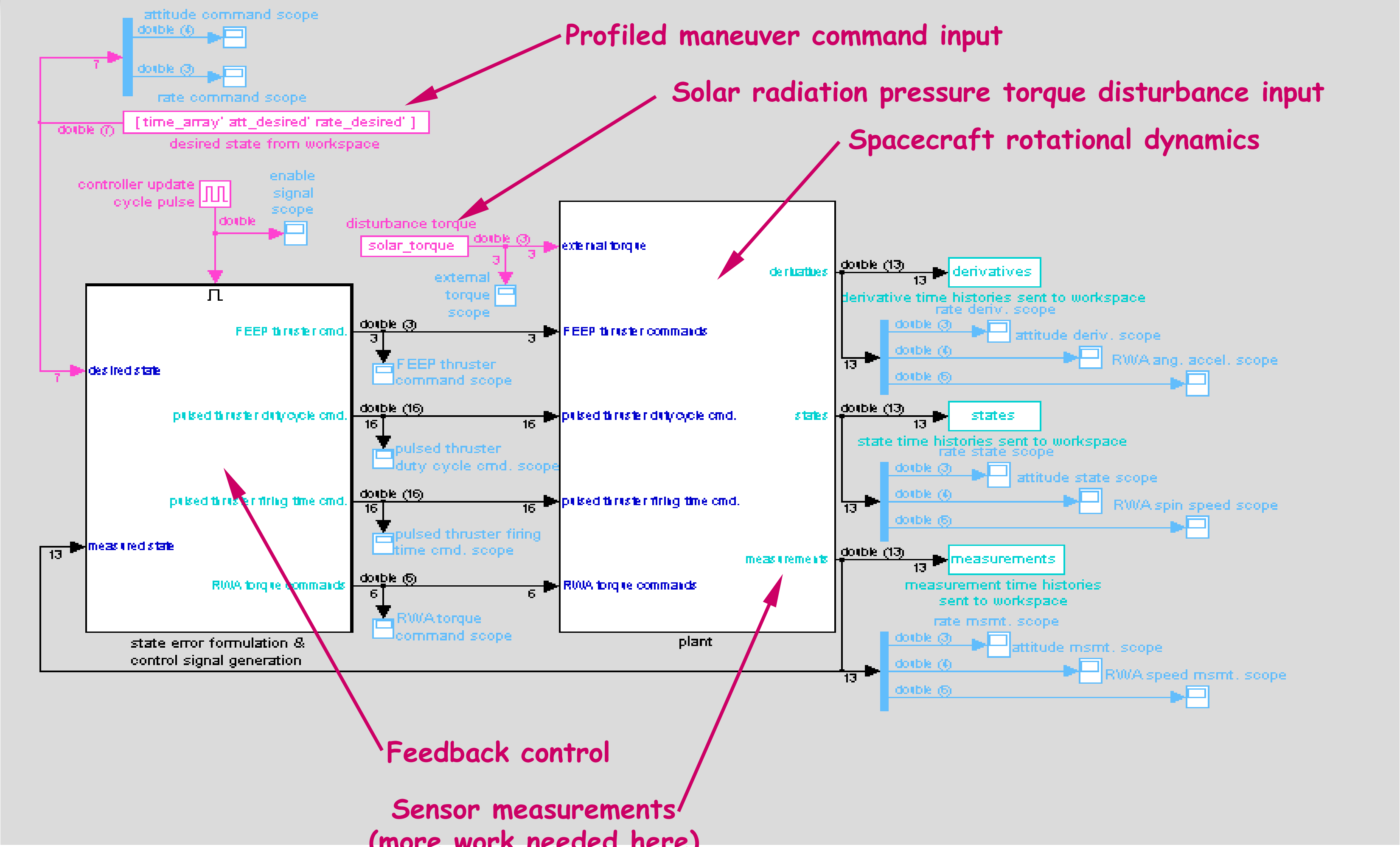




Commanded Torque (Expressed in Spacecraft Reference Frame)



# Overview of MATLAB/Simulink ADCS Model



Profiled maneuver command input

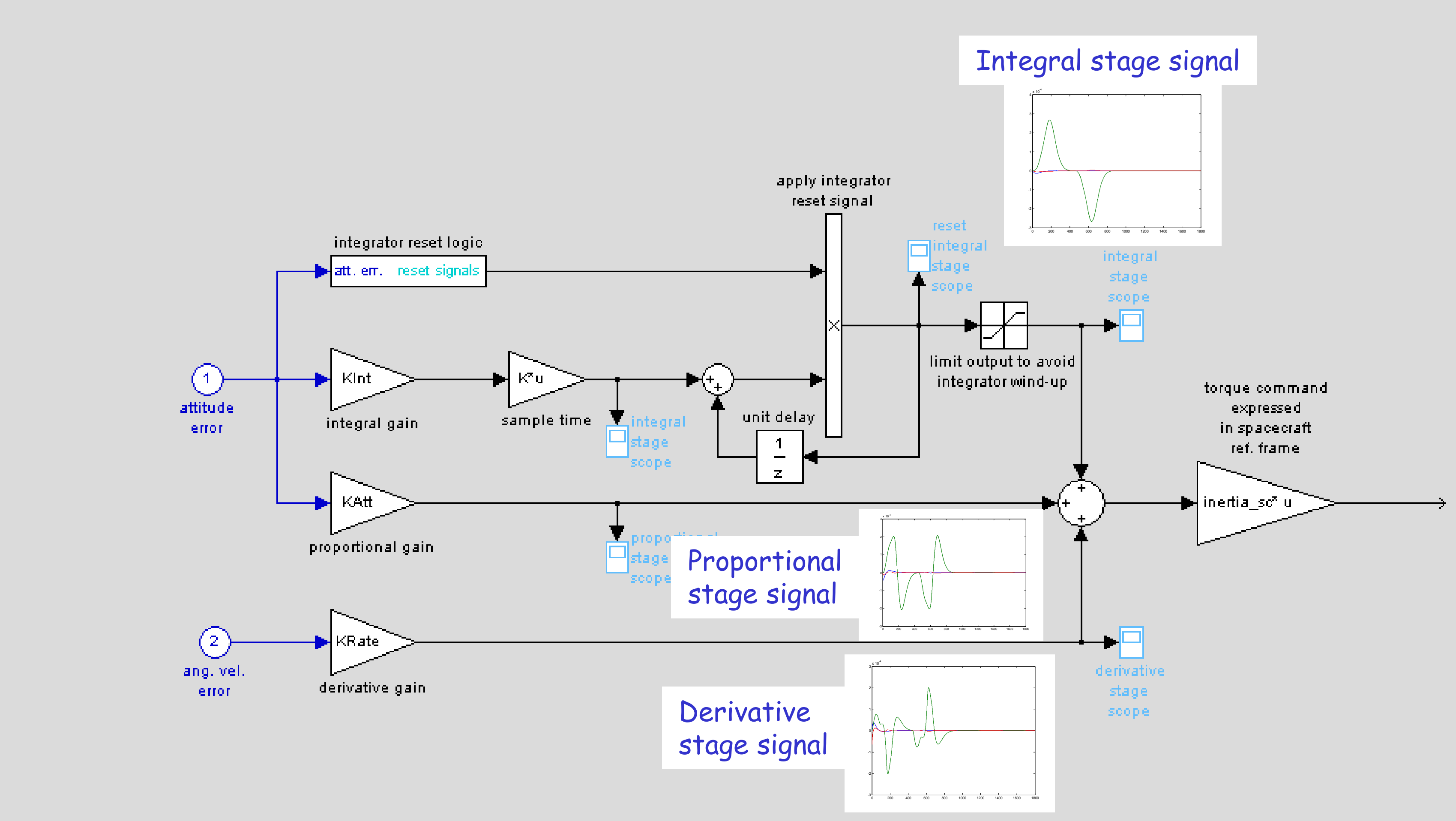
Solar radiation pressure torque disturbance input

Spacecraft rotational dynamics

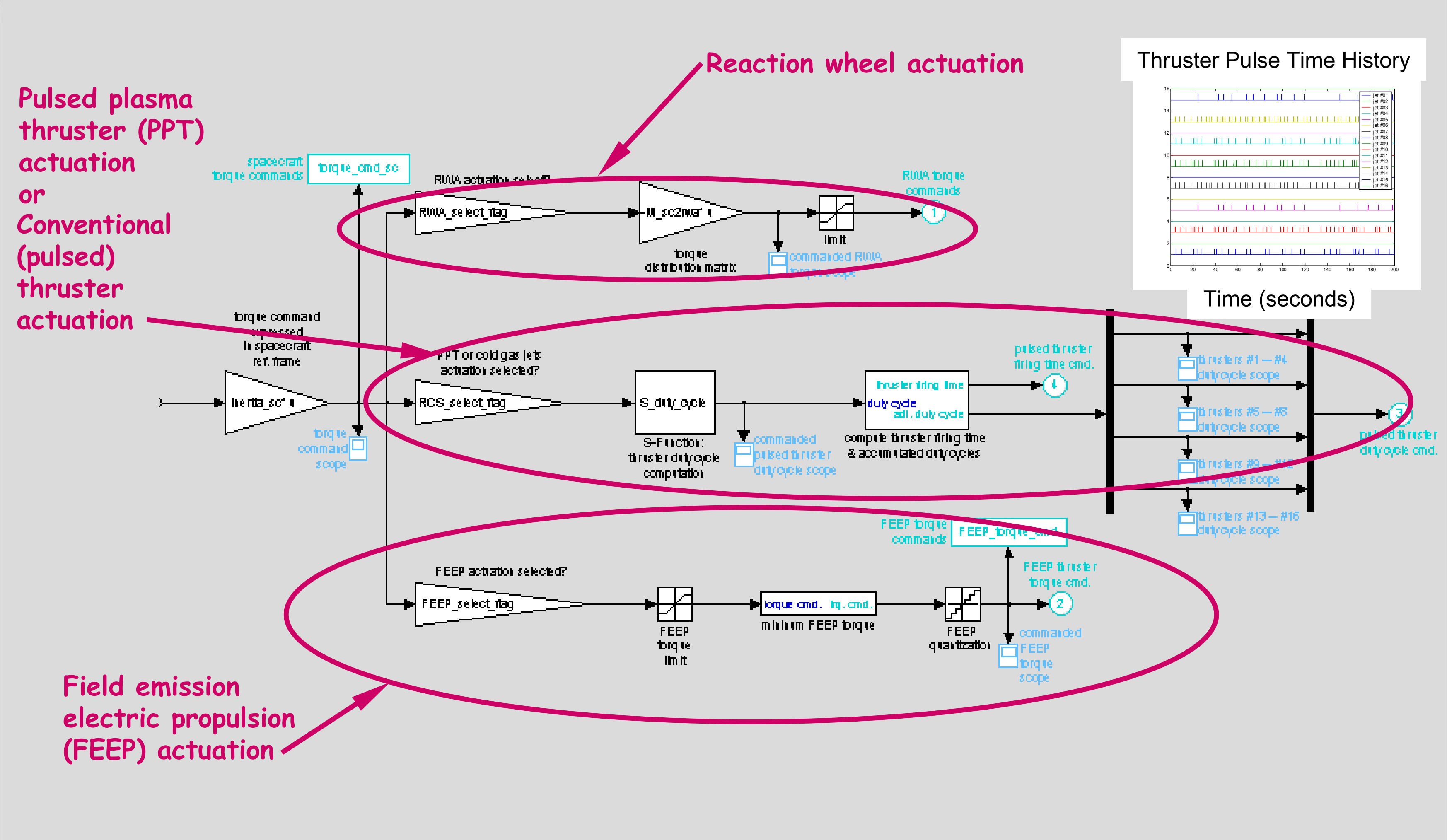
Feedback control

Sensor measurements
(more work needed here)

# *ADCS Uses Standard Controller Design (PID -- Proportional, Integral, Derivative)*



# Simulation Provides Models of Reaction Wheels and Multiple Thruster Types



Reaction wheel actuation

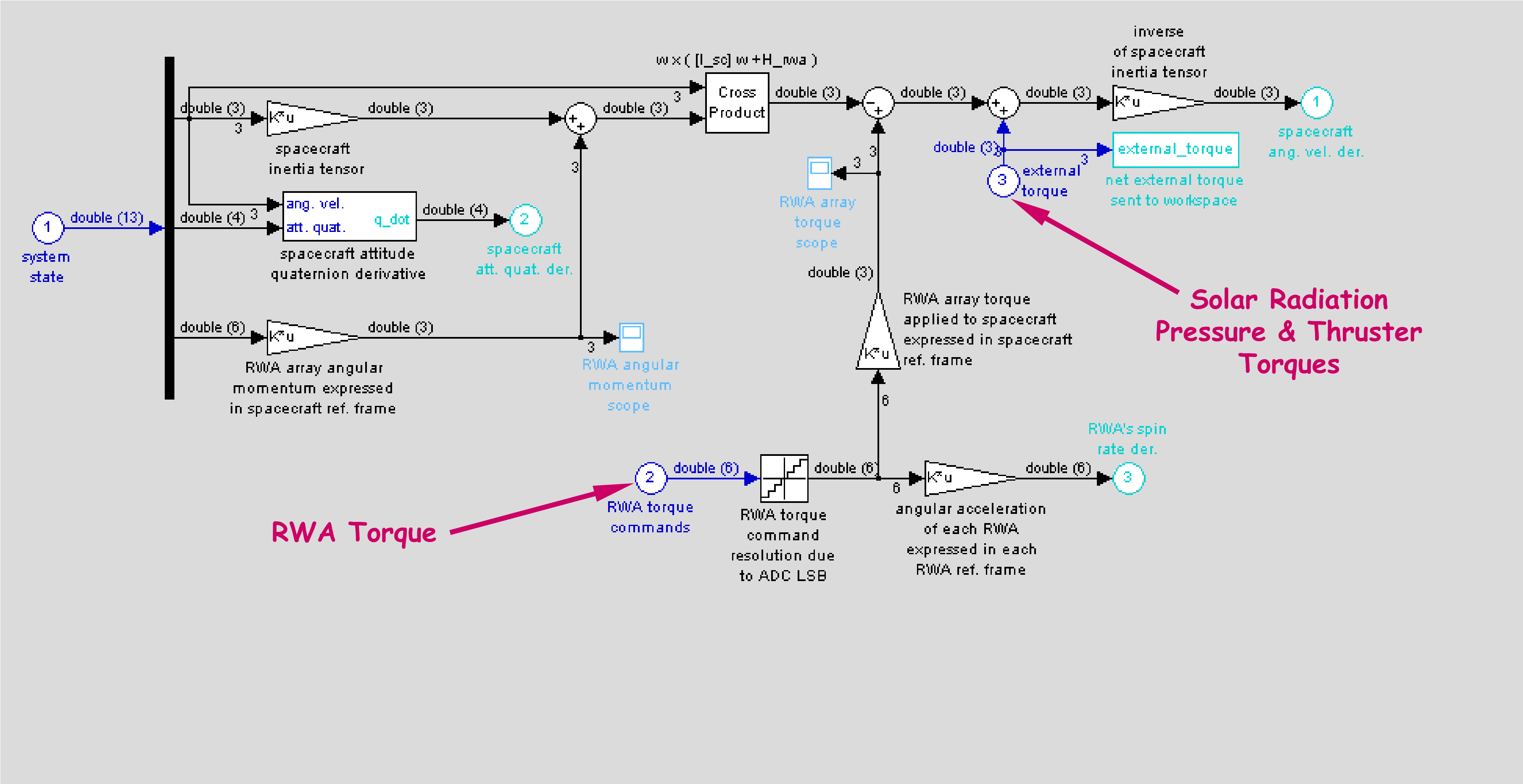
Pulsed plasma thruster (PPT) actuation or Conventional (pulsed) thruster actuation

Field emission electric propulsion (FEEP) actuation

Thruster Pulse Time History

Time (seconds)

# Simulation Models Spacecraft Dynamics With RWA and External Torque Inputs



**Solar Radiation Pressure & Thruster Torques**

**RWA Torque**

# Overview of The Propulsion Subsystem


Centrospazio FEEP


General Dynamics HCT

## Design Drivers

- De-tumble Maneuvers, Safing Maneuvers, Momentum Unloading, and Trajectory Correction Maneuver (TCM)- Requires ~ 250 m/s
- Attitude Control Trades looked at Electric Propulsion (EP) Options
  - FEEPS and PPTs for control options instead of RWA/Isolator (look at HCT's in future trades)
  - Electric Propulsion (EP) may prove advantageous if Mass becomes more of an issue ( Improve Mass Margin on Lower Cost Atlas V 551)
  - Initial Simulations Show FEEP disturbance level very low – however current simulations show that RWA/Isolators meet requirements
  - Currently EP not required

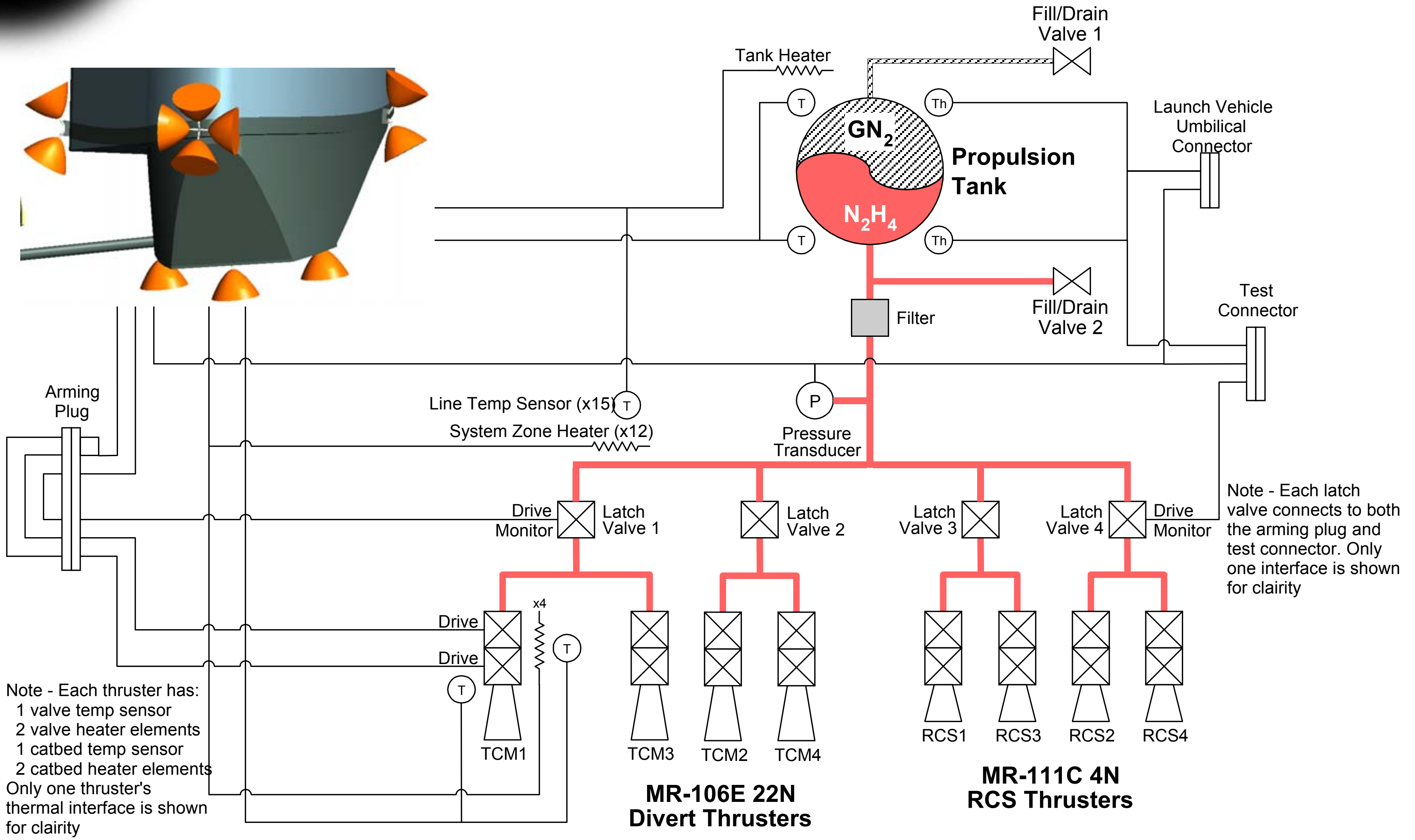
## Design Options

- Simple Hydrazine System Chosen for initial approach
- Large Launch Margin of Delta IV does not require high Isp propulsion


General Dynamics PPT


General Dynamics Monopropellant Thruster

# *Simple Heritage Hydrazine Propulsion System Meets Current Requirements*



**MR-106E 22N Divert Thrusters**

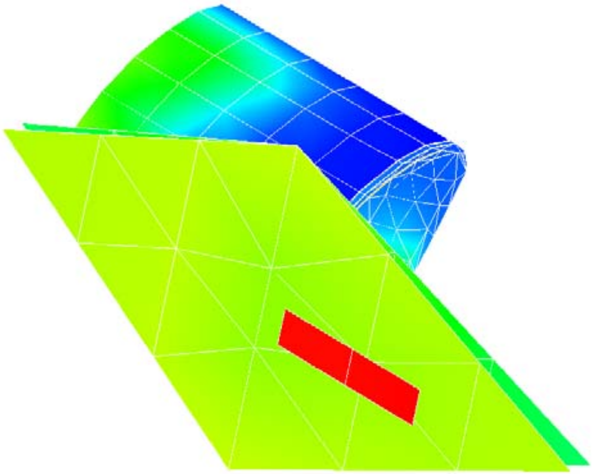
**MR-111C 4N RCS Thrusters**

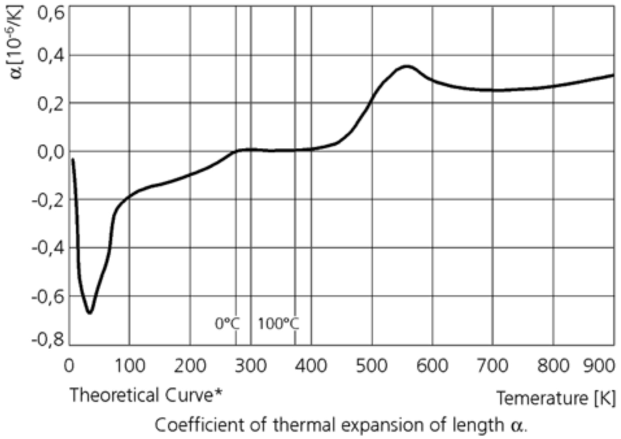
Note - Each latch valve connects to both the arming plug and test connector. Only one interface is shown for clairity

Note - Each thruster has:
- 1 valve temp sensor
- 2 valve heater elements
- 1 catbed temp sensor
- 2 catbed heater elements

Only one thruster's thermal interface is shown for clairity

# Summary of Initial Design of Thermal Control Subsystem

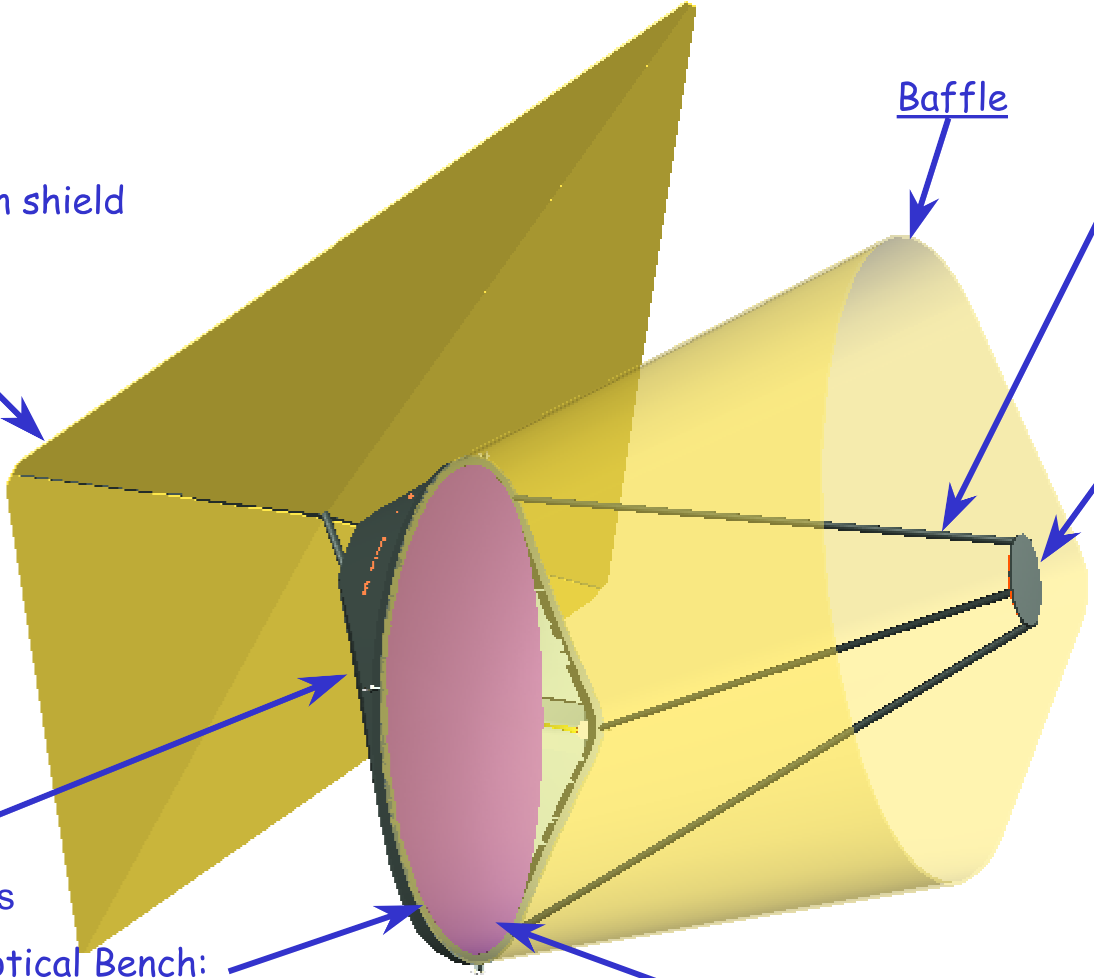




**ZERODUR® CTE Curve**

- Thermal Design Provides Accurate Control over Primary Mirror Temperature variations
  - Spatial variations (over 24-hour cycle) Controlled to within 0.03 °C
- Without full Sunshield, Primary Mirror Spatial variations Exceed 0.12 °C
- Active Heater Control of Optical Bench is Required - Passive Design Would Result in Primary Mirror Temperatures of -140 °C
- Primary Mirror Operating Temperatures of 0 °C are Favored: Simplifies Manufacturing Testing & Calibration. Also at 0°C CTE (Coefficient of Thermal Expansion) of ULE, Zerodur are Minimized
- Active Heating Provides Precise Control over Primary Mirror Temperature Gradients - Bench Heater Power Requirement ~ 700 W

# Overview of the TPF Coronagraph Thermal Design



Sunshield:
NGST-style radiation shield

Baffle

Struts:
Thermally isolated from Bench

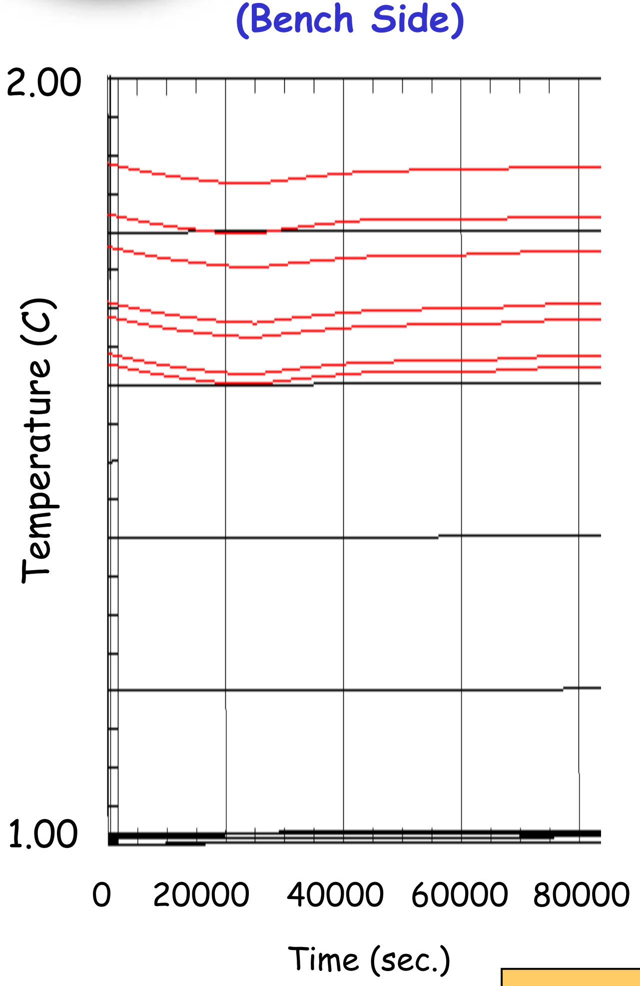
Secondary Mirror:
MLI-covered Space-facing surfaces

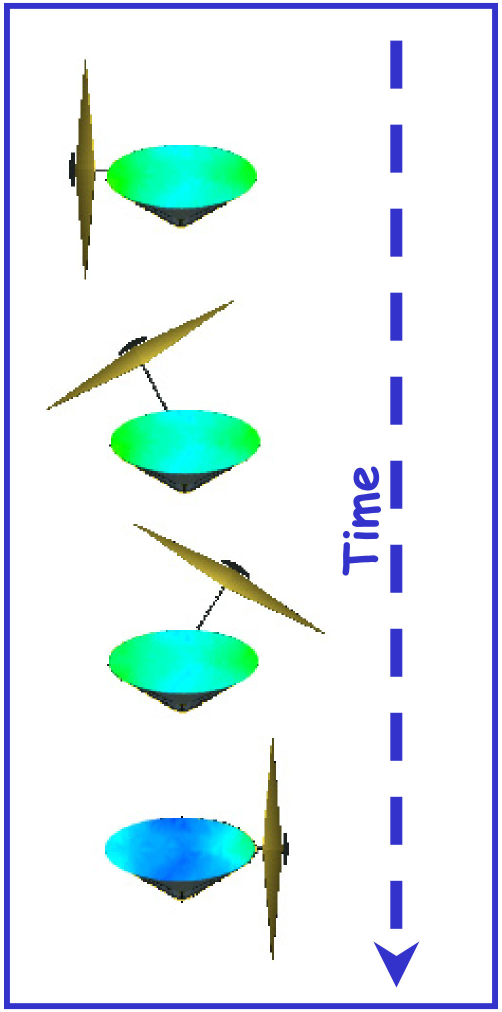
Spacecraft Bus:
High-Conductivity Facesheets and Beams

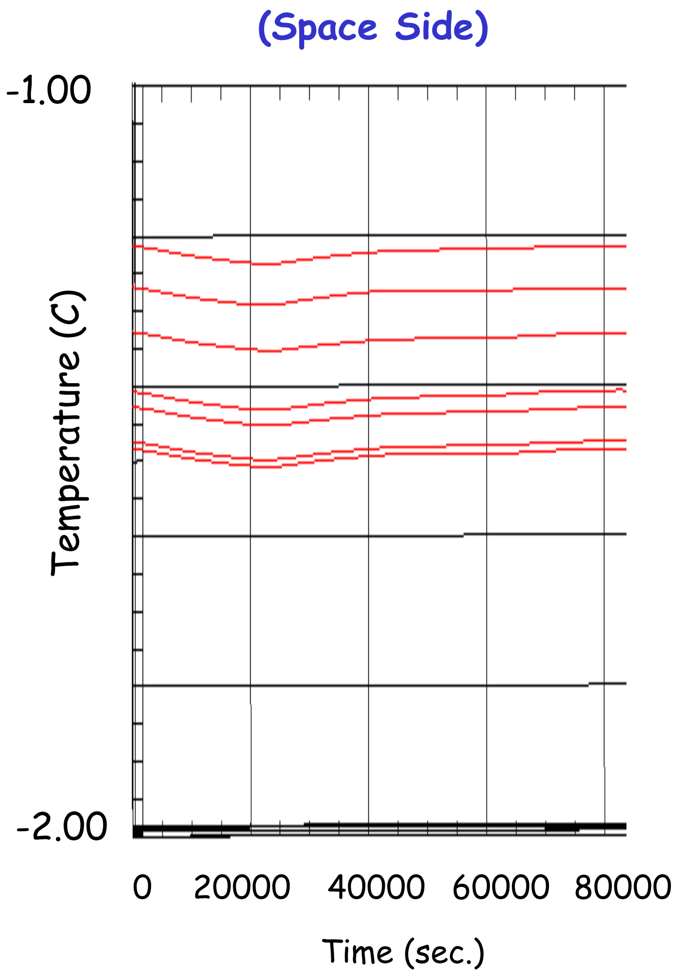
Optical Bench:
Thermally Isolated from Bus
Actively Controlled Heaters
Primary Heat Path to Primary Mirror

Primary Mirror:
Conducts to Bench via Actuators
Radiates to Bench

# Primary Mirror Temperature Gradients over 24-hour Observational Period

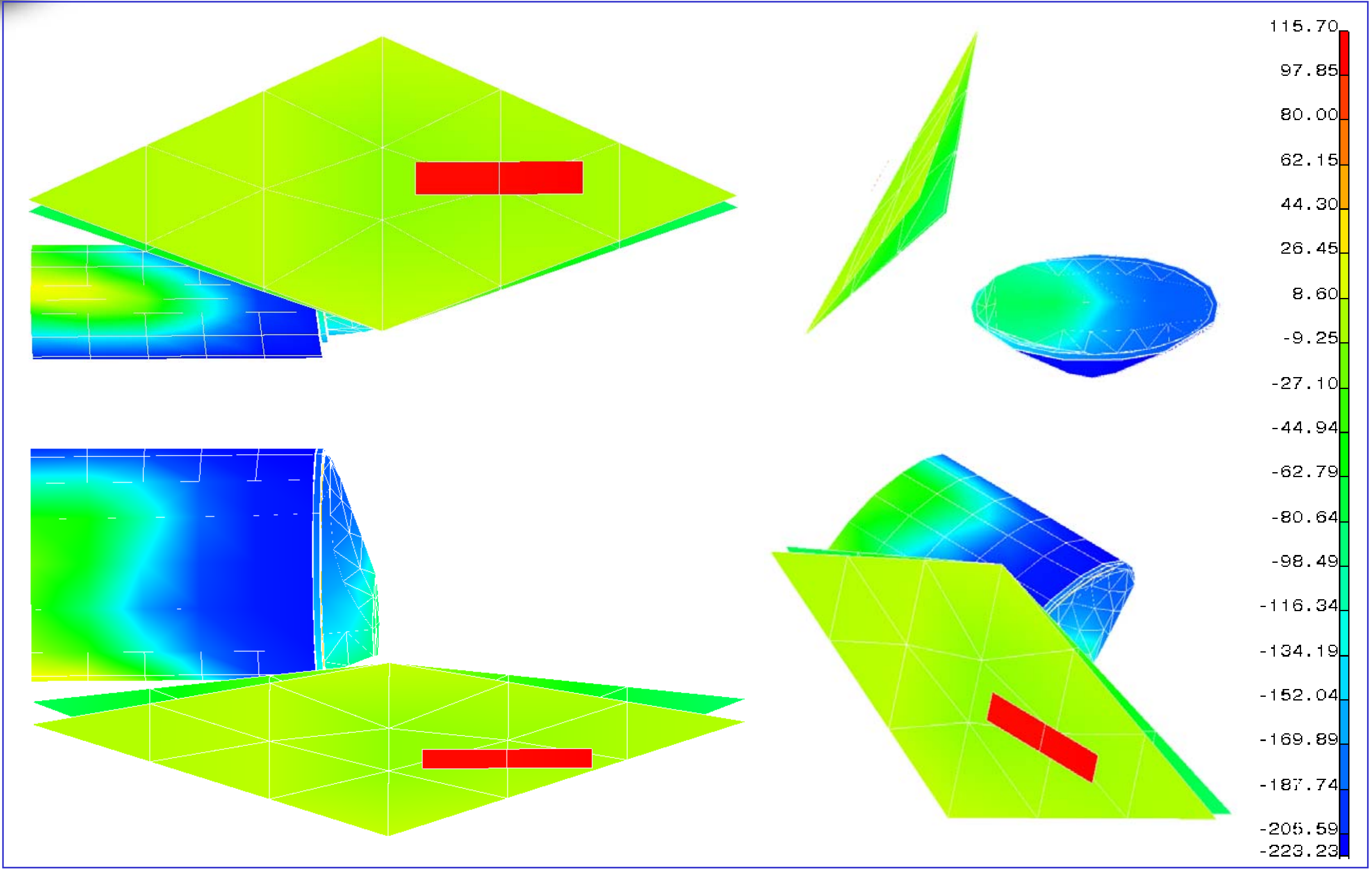






Represents Worst-Case Solar Excursion

# External Temperature Contours of the TPF Coronagraph with Sunshield



# *Follow-on Work is Likely to Produce even Lower Temporal Gradients*

## Thermal Finite-Element Model - Higher Fidelity Thermal & Structural Model

- Optimization of Nodes/Elements for Detailed Analysis of Thermal Gradients
- Incorporate Intelligent Software Control of Bench Heaters into Thermal Model
- Complete Ray-Tracing Analysis of Specular Radk's (Including NGST-Style Sunshield)

## Development / Testing

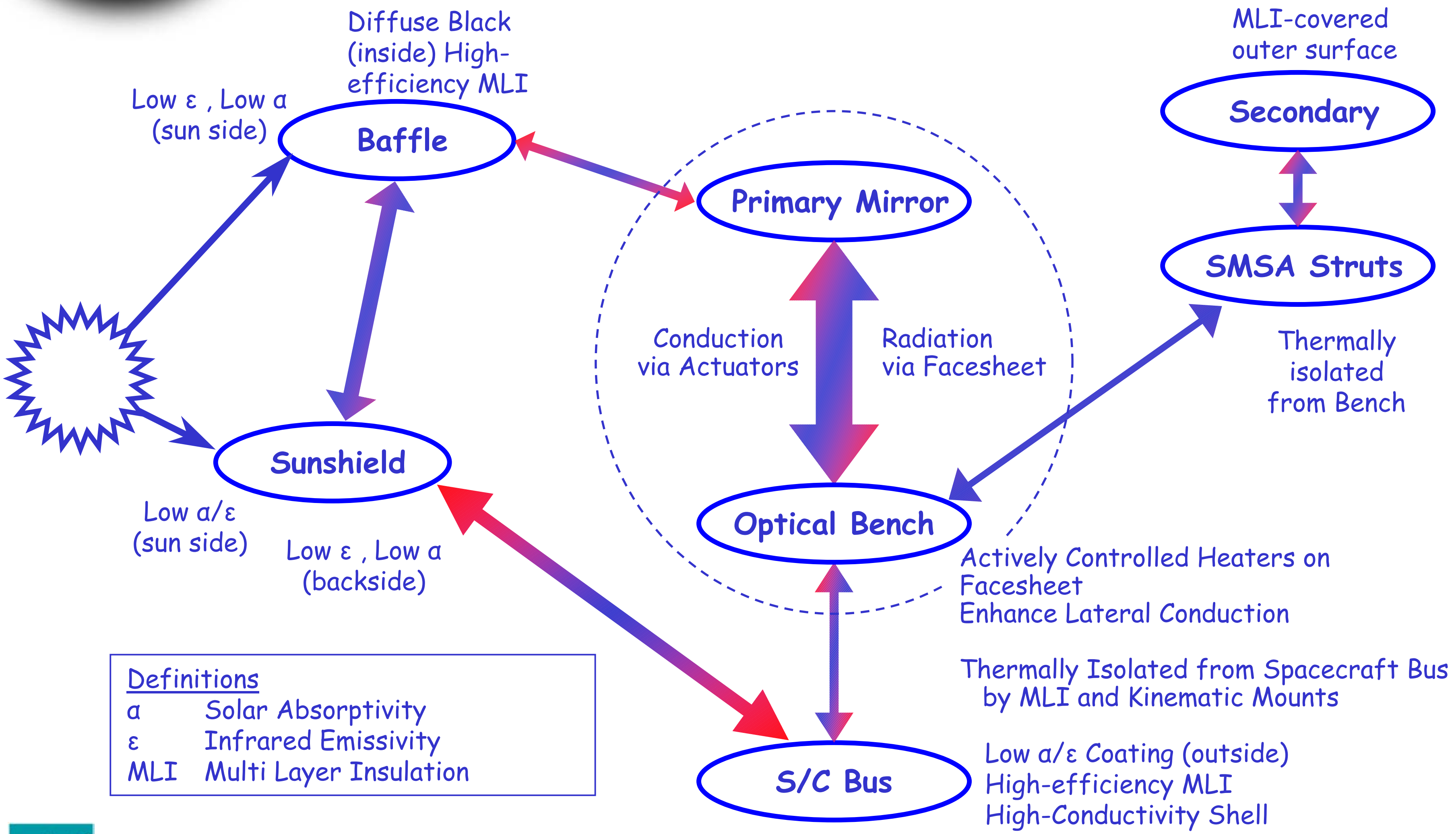
- Development Tests of Optical Bench Active Heater Control System
- Hardware Testing of Conductive Paths through Actuators, Isolators, and Couplings
- Use of Anisotropic Composite Materials in Spacecraft Bus and Optical Bench

## Future Trade Studies

- Refined Baffle and Sunshield Design including
  - Optimization of Optical Properties
  - Additional Layers
  - Geometry Optimization
- Selection of Primary Mirror Material: ULE, Zerodur, Fused-Silica
- Low-Temperature Primary Mirror Operation Using Unique Fused-Silica CTE Curve
- Enhanced Conduction through Mechanical Actuators Could Lower Bench Temperature

Temporal Thermal Gradients - Top Ten Issue for the Coronagraph

# Thermal Design Minimizes Temperature Gradients on Primary Mirror and Bench



Definitions

| | |
|---|---|
| α | Solar Absorptivity |
| ε | Infrared Emissivity |
| MLI | Multi Layer Insulation |

# Overview of the Optical Bench Thermal Control System

Bench is Thermally Isolated from Spacecraft Bus and SMSA Struts

- Conduction Heat Transfer Minimized through Kinematic Mounts
- Multi-Layer Insulation Isolates Bench from Bus, Electronics, and Optics

Facesheet Bonded to Optical Bench Lattice Provides Multiple Benefits

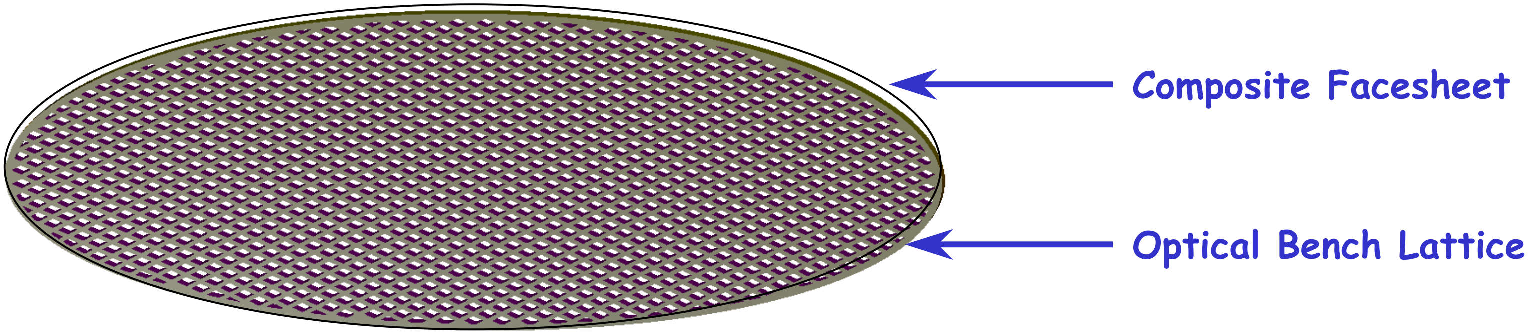
- High-Emissivity Thermal Coating Enhances Radiative Heat Transfer to Primary Mirror
- High Thermal Conductivity Facesheet Assists in Isothermalization of Bench

Active Heater Control

- Active (Software) Control of Facesheet Local Temperature to within 0.10 °C
- Thin-Film Kapton Heaters Bonded to Facesheet

Optical Bench Provides a Means of Control over Primary Mirror Temperature

- Primary Mirror Must be Heated to 0 °C due to Unique CTE Curve
- Precise Control of Primary Mirror to within 0.04 °C



# TPF Thermal Model Predictions for Several Sun Shield Configurations

**Component Temperature Predictions for 24-hour Period, (C)**

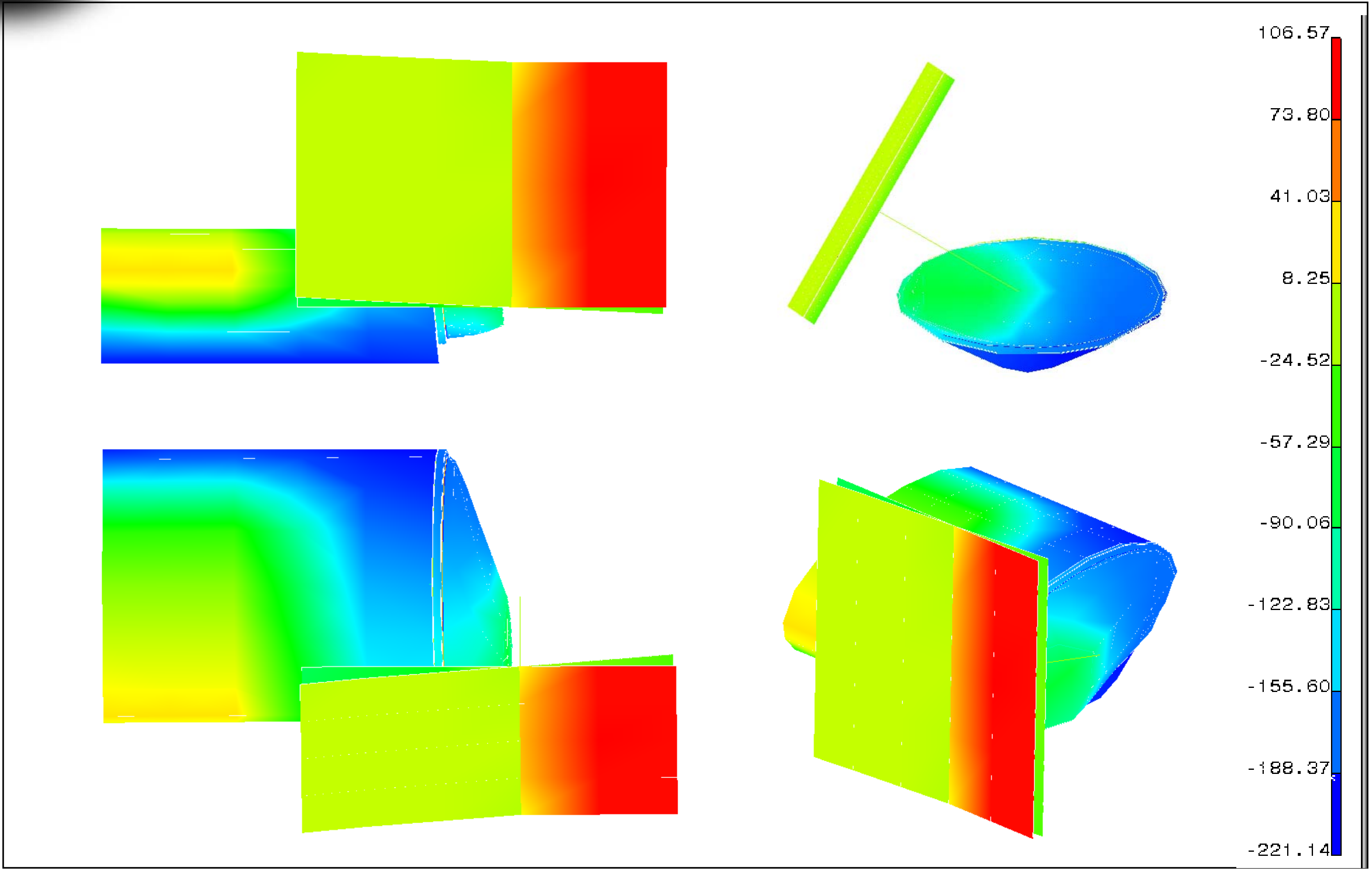
| | **Full Sunshield** | | Partial Sunshield | | No Sunshield | |
|---|---|---|---|---|---|---|
| | **(Max.)** | **(Min.)** | (Max.) | (Min.) | (Max.) | (Min.) |
| **Spacecraft Bus** | **-80** | **-191** | -72 | -187 | 7 | -172 |
| **Baffle - Exterior** | **37** | **-223** | 37 | -221 | 37 | -221 |
| **Baffle - Interior** | **-125** | **-165** | -124 | -164 | -122 | -163 |
| **Optical Bench** | **50** | **49.1** | 50 | 49.1 | 50 | 49.1 |
| **SMSA Struts** | **-129** | **-151** | -128 | -149 | -127 | -149 |
| **Secondary Mirror** | **-164** | **-164** | -163 | -163 | -162 | -162 |
| **Primary Mirror** | **1.94** | **-1.75** | 2.02 | -1.69 | 2.19 | -1.57 |
| **Lateral Gradient** | *** 0.53** | | * 0.60 | | * 0.60 | |
| **Thru Gradient** | *** 3.10** | | * 3.10 | | * 3.10 | |
| **Dynamic Gradient** | *** 0.03** | | * 0.04 | | * 0.12 | |

**(* Denotes Temperature Gradient)**

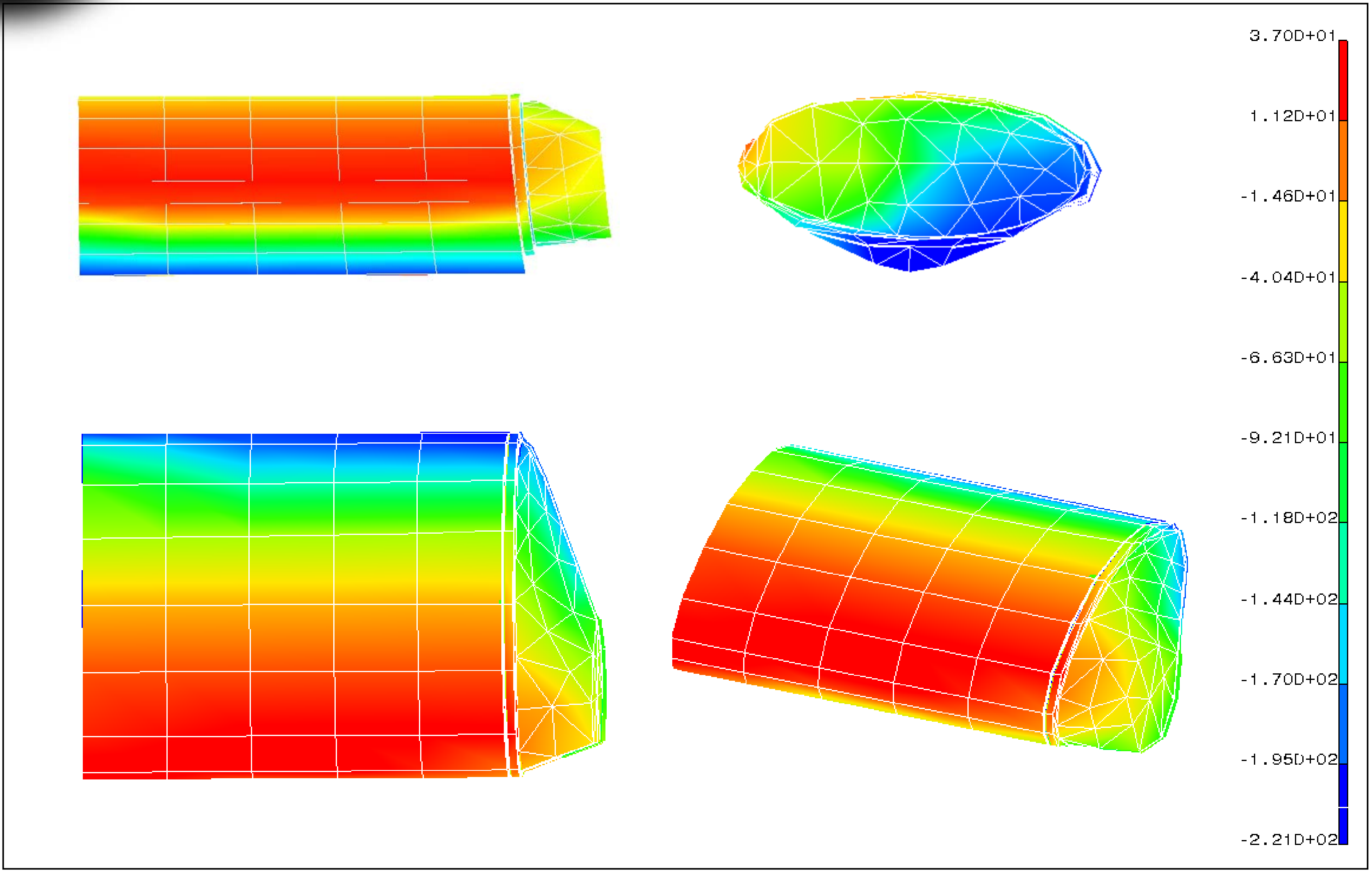
# Backup Thermal Slides

**Additional Analysis...**

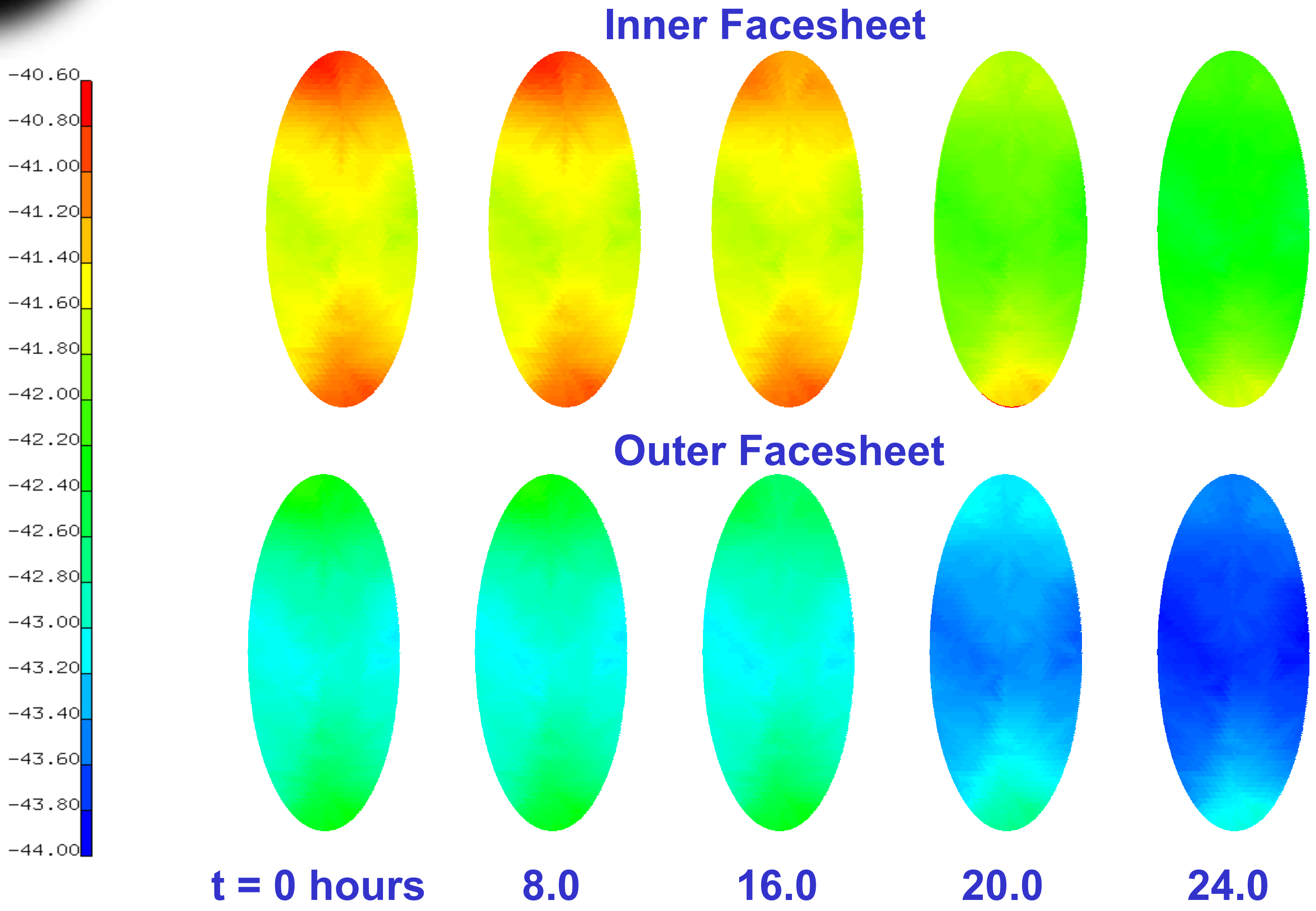
# TPF Coronagraph with Sunshield Temperature Contours



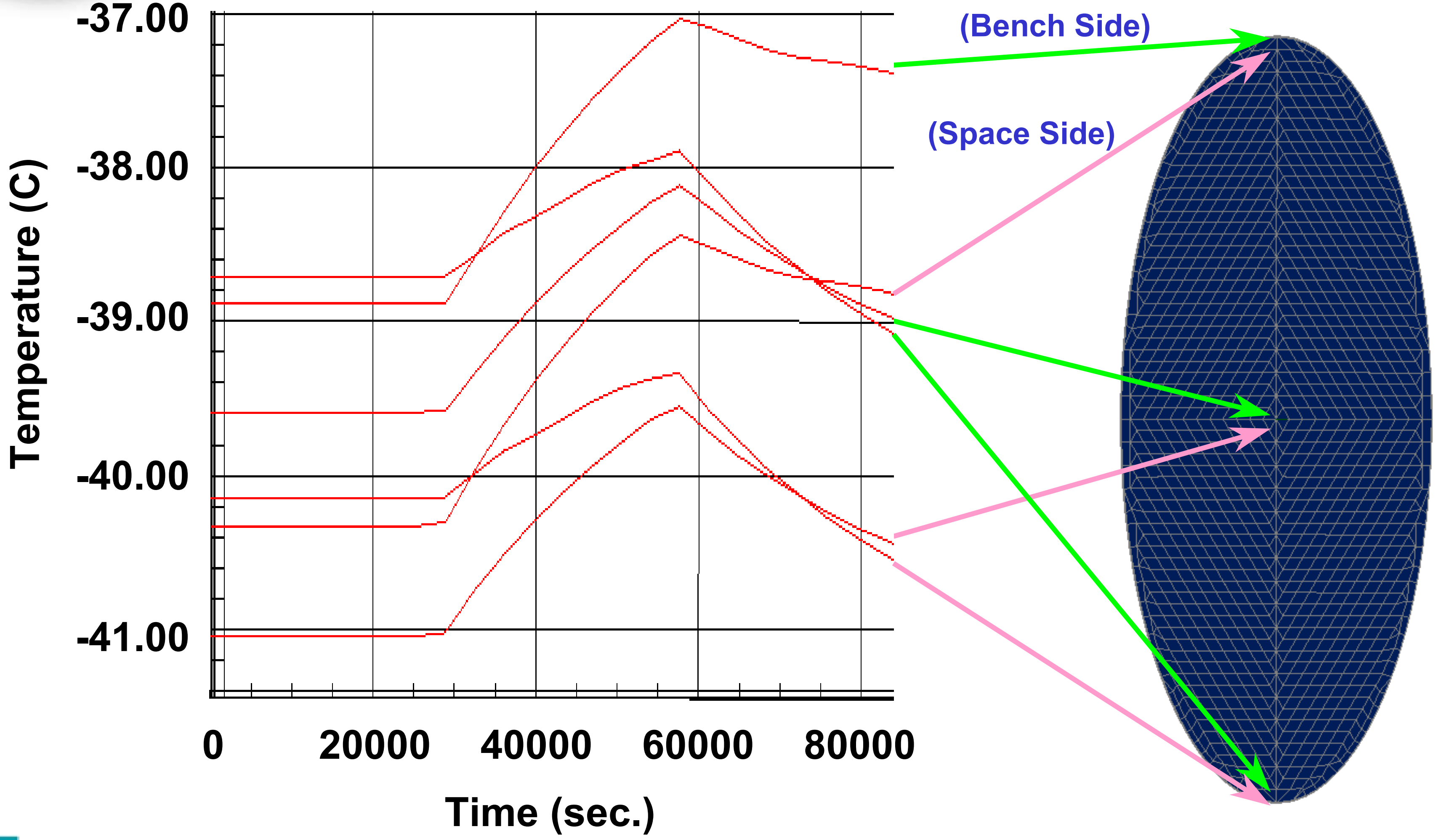
# NO Sunshield, Bench Heated to 50 C: Temperature Contours



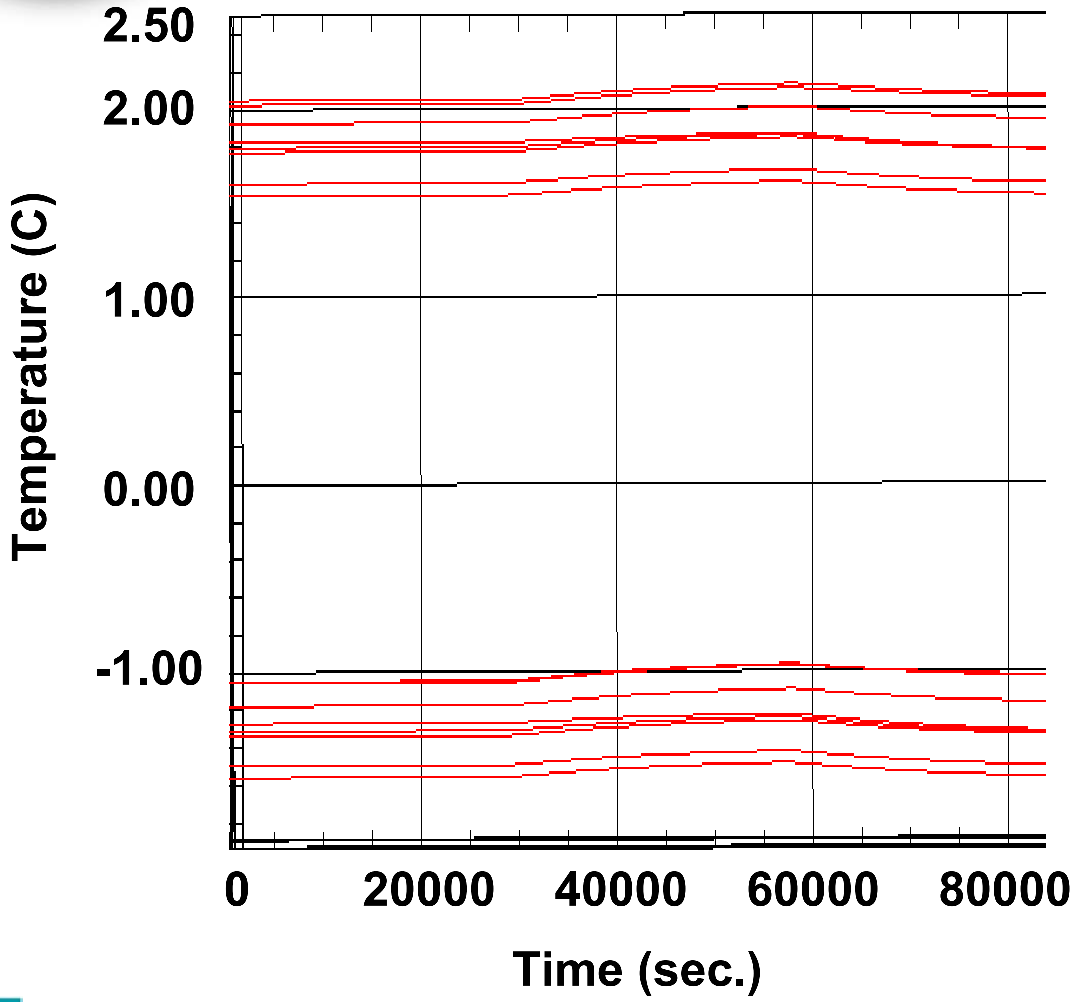
# *NO Sunshield, Bench Heated to **30 C**:*
# ***(SCT Baffle)** Primary Mirror Temperatures*
# ***bench-primary e*vf=0.30***

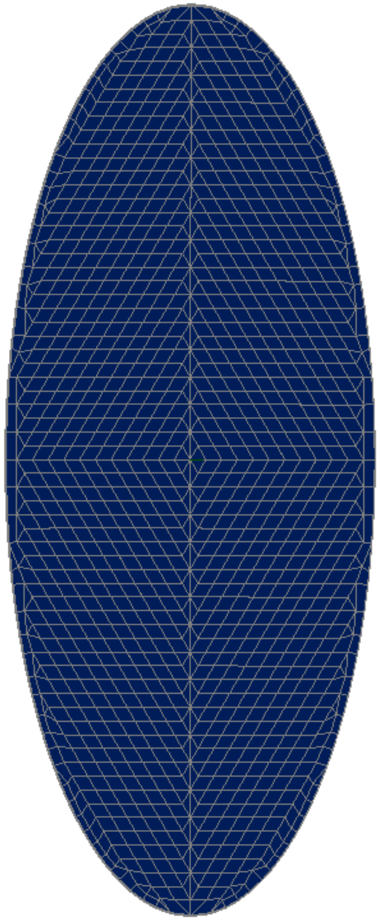


# NO Sunshield, Bench Heated to **30 C**: **(SCT Baffle)** Primary Mirror Temperatures **bench-primary e*vf=0.30**

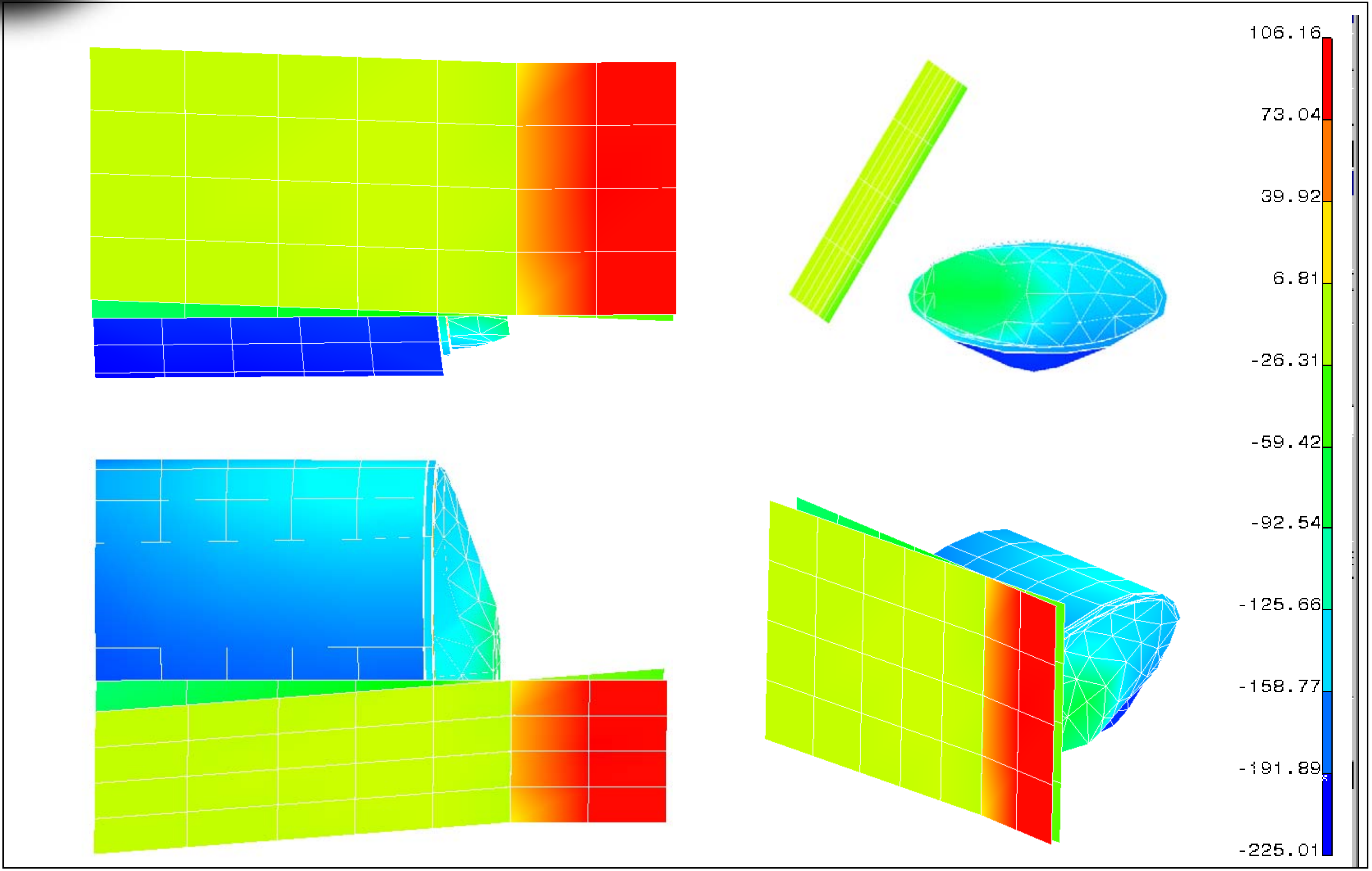


# *No Sunshield, Bench Heated to **50 C**: **(VDA Baffle)** Primary Mirror Temperatures **bench-primary e*vf=0.90***

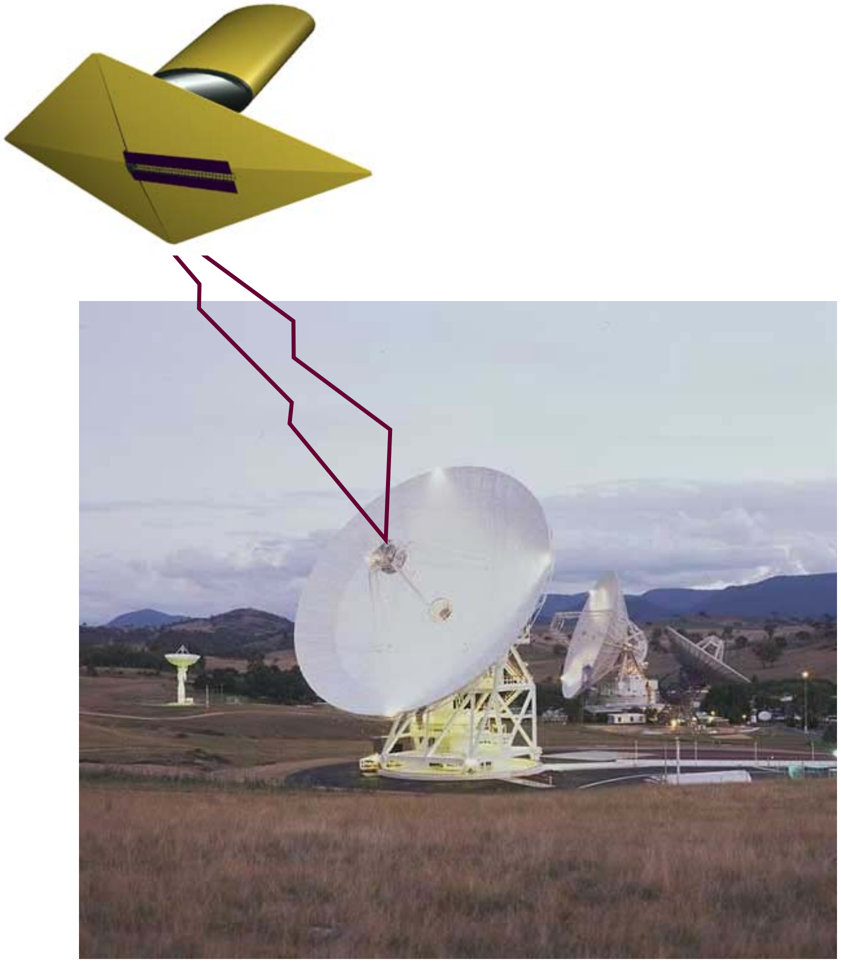




# Full Sunshield, Bench Heated to 50 C: Temperature Contours



# Summary of The Telecommunication Subsystem



- Dual telecommunications systems
  - Ka-Band for downlink of scientific information Maximum data rate is 8 Mbps
  - X-Band for downlink of spacecraft engineering telemetry Estimated data rate is 5 kbps
- Utilize the Deep Space Network (DSN) 34m Ground Station
- Use current configuration of General Dynamics (Motorola) Small Deep Space Transponder (SDST)
- Observatory and Ground segment designed to be capable of at least 8 hours per day/ 7 days a week uplink and downlink communications
- Full redundancy in all critical hardware

# Telecommunication Subsystem

- Provides interface between the spacecraft and the Deep Space Network (DSN) 34m BWG Station
  - X-Band and Ka-Band compatibility will be available
- Observatory and Ground segment shall be capable of at least 8 hours per day/ 7 days a week uplink and downlink communications
- Spacecraft is currently set for earth-trailing orbit
  - Maximum earth range is 0.2 AU (≈30M km)
- Mission design life is 5 years
  - Possible extension to 10 years
  - Full redundancy in all critical hardware
- Downlink science and engineering data volume approximately 232 Gbits
- Link margin is +3 dB minimum for uplink and downlink
  - Command links calculated using bit error rate (BER) of less than $10^{-5}$
  - Telemetry links calculated using BER of less than $10^{-6}$
- Can use current configuration of General Dynamics (Motorola) Small Deep Space Transponder (SDST)

# Telecommunications Subsystem Downlink Description

- Dual telecommunications systems is simple and efficient design
  - Separates science data from engineering telemetry
- Ka-Band for downlink of scientific information
  - Uses 60W Ka-Band TWTAs
  - SDST-external x4 multiplier to generate Ka-Band frequency
  - Uses high gain antenna (HGA) with 42.88 dBic of gain
    - Gain value based on parabolic dish parameters with $\eta$=55%
      - Multiple options available
  - Maximum data rate is 8 Mbps
      - Maximum data rate capability of SDST is ≈ 10Mbps
  - Estimated data volume for science data of > 230Gbits in 8 hours period
  - All components have extensive deep space heritage
      - 60W Ka-Band TWTA will have space heritage by 2006
- X-Band for downlink of spacecraft engineering telemetry
  - Uses medium gain antenna (MGA) of 16 dBic gain collocated with HGA
    - Gain value based on horn type antenna
  - Requires only 15W Solid State Power Amplifiers
  - Estimated data rate is 5 kbps
  - Allows for downlink of engineering data at any time without the need to downlink science data
  - All components have extensive deep space heritage
- An X-Band high data rate contingency mode as a Ka-Band backup has not been considered due to the high downlink data volume

# Telecommunications Subsystem Uplink Description

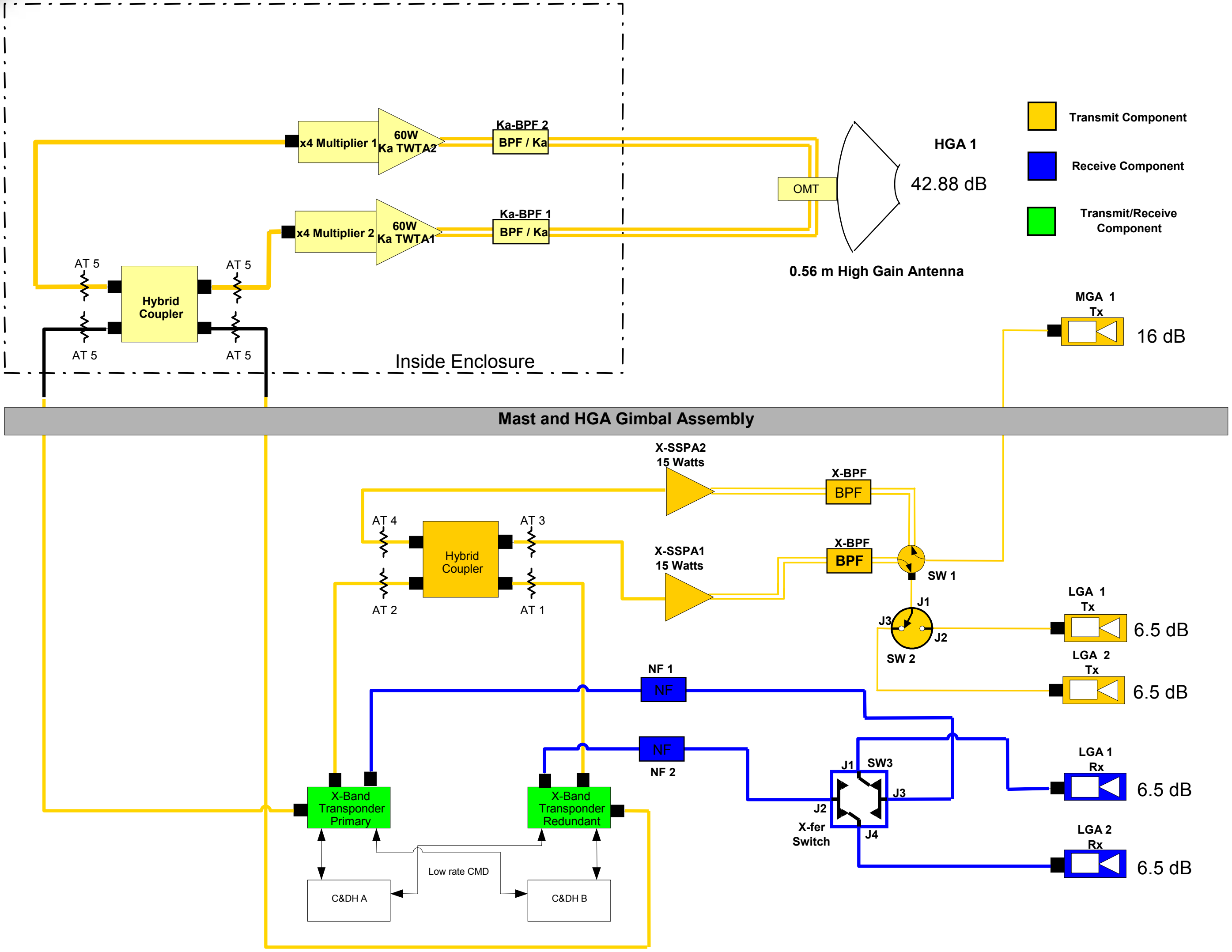
- X-Band low gain antennas (LGA) used for uplink
  - Allows simultaneous uplink during downlink
- Provides 2 areas of $2\pi$ steradian coverage
- Allows for uplink data rate of 2000bps at maximum earth range
- All components have extensive deep space heritage

# Telecommunication Margin Summary

| Downlink Margins using DSS-25 34m BWG Antenna | | | | | |
|---|---|---|---|---|---|
| | | | Link Margin (dB) | | |
| | Data Rate | Range (AU) | LGA | MGA | HGA |
| Engineering Data (X-Band) | 40 bps | 0.2 | 14.83 | - | - |
| | 100 bps | 0.2 | 11.93 | - | - |
| | 252 bps | 0.2 | 8.86 | - | - |
| | 2.1 kbps | 0.2 | - | 6.69 | - |
| | 5.0 kbps | 0.2 | - | 3.19 | - |
| Science Data (Ka-Band) | 40kbps | 0.2 | - | - | 26.13 |
| | 2Mbps | 0.2 | - | - | 9.14 |
| | 4Mbps | 0.2 | - | - | 6.13 |
| | 6Mbps | 0.2 | - | - | 4.37 |
| | 8Mbps | 0.2 | - | - | 3.12 |

| Uplink Margins using DSS-25 34m BWG Antenna | | | | | |
|---|---|---|---|---|---|
| | | | Link Margin (dB) | | |
| | Data Rate | Range (AU) | LGA | MGA | HGA |
| Command Data (X-band) | 7.8125 | 0.2 | 33.32 | - | - |
| | 125 | 0.2 | 23.75 | - | - |
| | 500 | 0.2 | 17.73 | - | - |
| | 2000 | 0.2 | 11.71 | - | - |

# TPF Telecommunications Subsystem Block Diagram

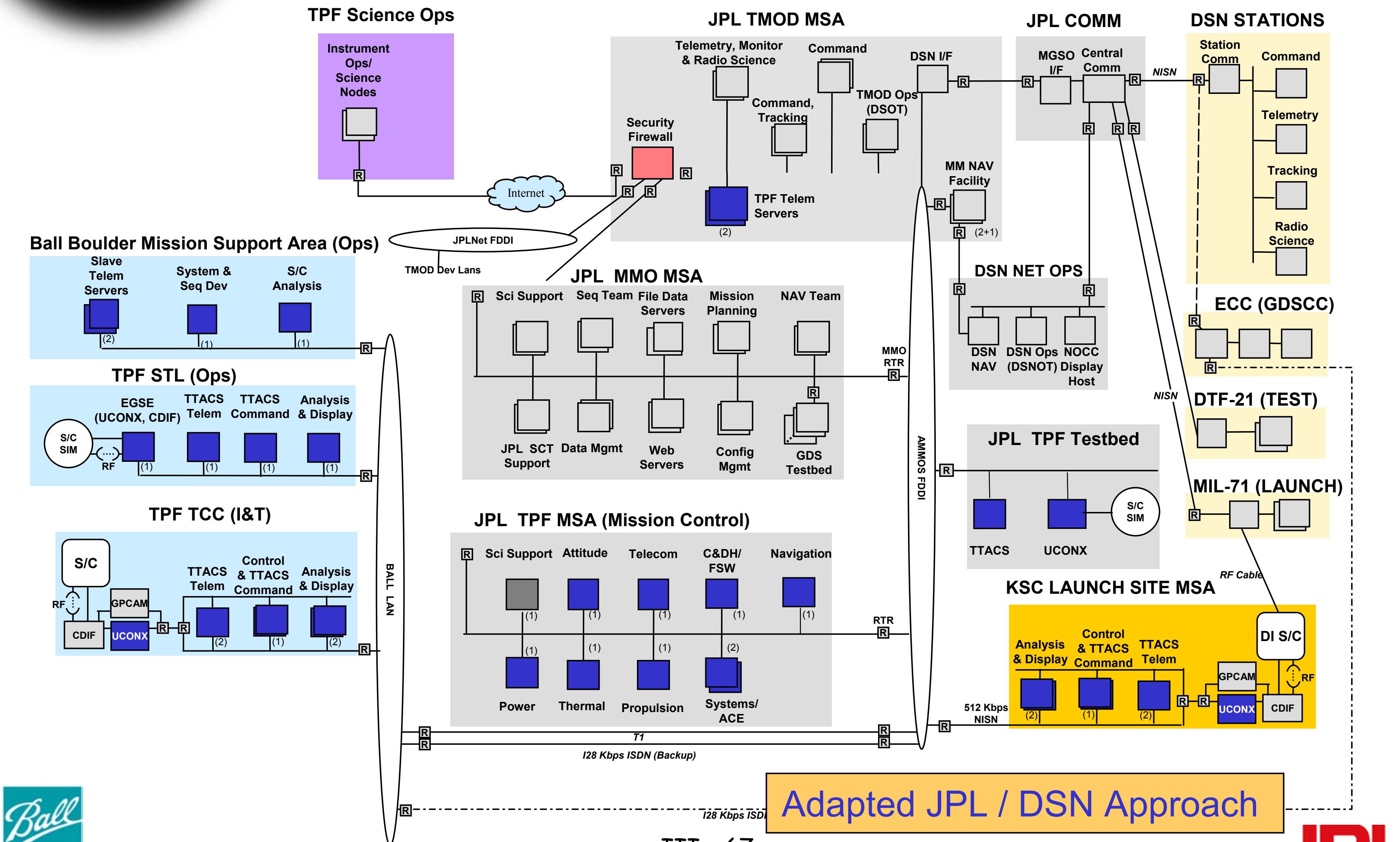


# Overview of Ground Segment Operations

- Mission Operations Centered at JPL (Mission Control)
- Science Operations Centered at Space Telescope Science Institute (STSI)
- Integrated Flight Team of JPL and BATC Personnel
- BATC Flight System and Subsystem Support
  - At JPL for High Activity events as appropriate
    - Post launch checkout, Calibration, ***New Earth Discovery***
  - From Boulder Mission Support Area for low activity
- Ground Operational Capabilities (e.g., AMMOS/GDS) and Interfaces Established Early and Used Throughout I&T and KSC Pre-launch Operations
- Examine Feasibility of Improved Autonomous Operations
  - Simple Tasking of Observatories for up to 2 Weeks of Autonomous Operations
- Existing/Planned Upgrades of TMOD Deep Space Mission System Services
  - 34M Array Capabilities at Goldstone (MADRID/CANBERRA TBD)
  - Planned Ka Band Upgrades

Based on Typical JPL / Ball Deep Space Operations

# TPF Coronagraph
# Ground Data System (GDS) Architecture



Adapted JPL / DSN Approach

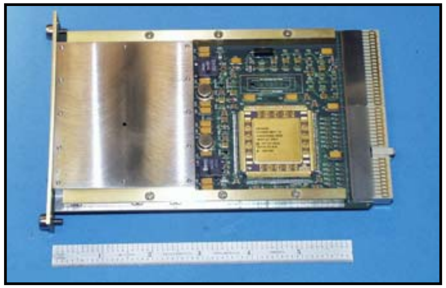
# *Overview of Command & Data Handling (C&DH)*

Spacecraft Control Unit

SBC PowerPC 750

2010

Moores Law



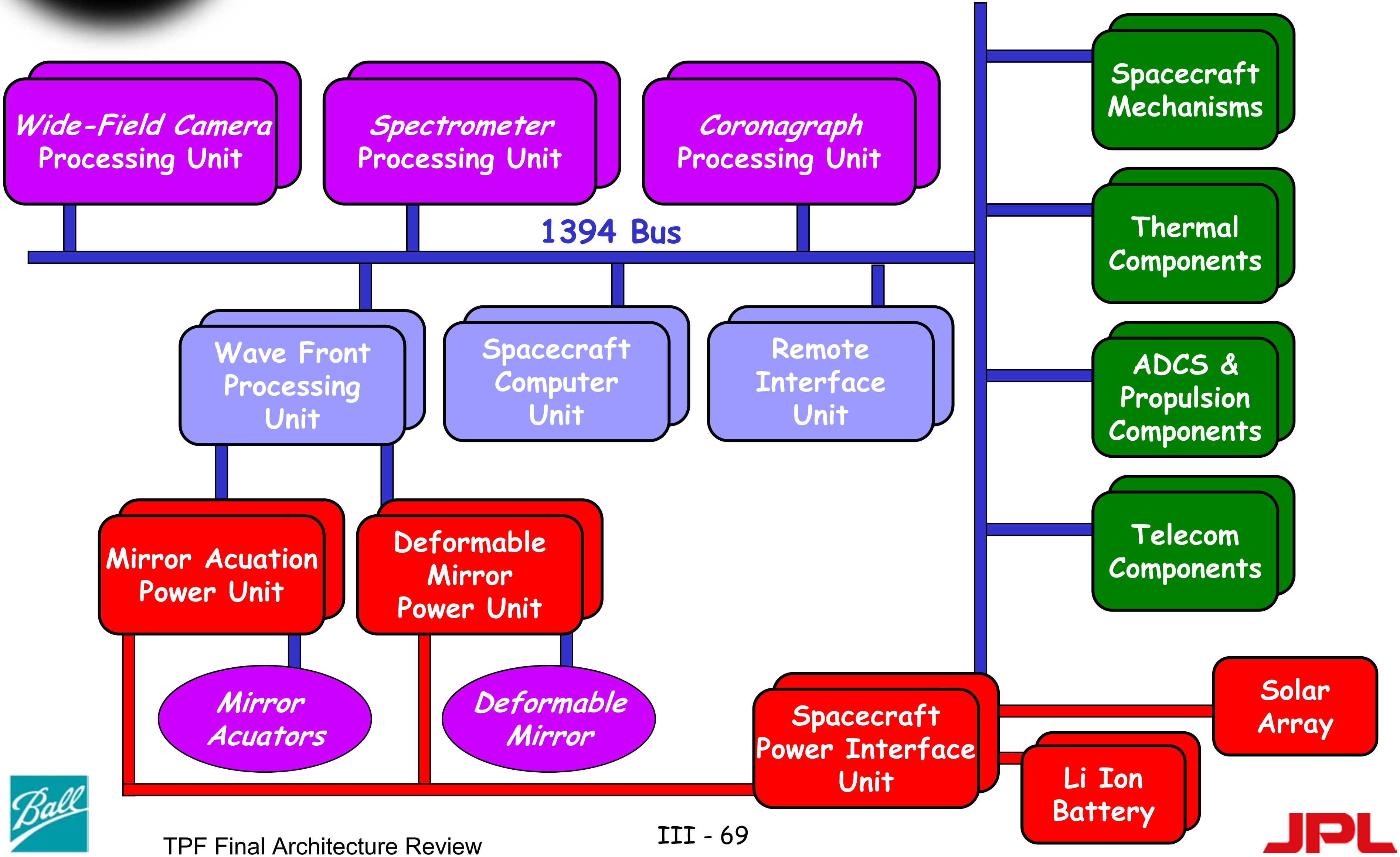
SEAKR NVM

Design Drivers

- Processor
  - Relatively High Processing Demands
  - Rad Hard Processors Available by 2010
- Data Storage
  - Compression needs?
- Reliability & Autonomy
- Modularity & Testability
- High Bandwidth between Spacecraft, Wavefront, and Science Instruments
  - Bus 1553/422 versus 1394
  - Increasing adoption of new networking technologies for S/C (i.e. IEEE-1394)

Existing Technology Sufficient However TPF will take advantage of emerging Technology

# TPF Coronagraph C&DH Block Diagram



# *Summary of Flight Software (FSW) Design Drivers*

Observatory Operation

- Majority of the operations will require significant processing
- Deformable mirror settings
- Fine Steering Mirror will require high throughput and ADCS integration
- Operation of the Sun Shield will require high close integration with ADCS
- Science Data Processing , Storage, and Transmission

Attitude Determination & Control System (ADCS)

- ADCS bandwidth requirements will place high demands on system
- Detector data processing in conjunction with ACS processing and component commanding will require special attention

Autonomous Operations

- Increased autonomous operation and application of high-level languages will present increased processing demands over previous systems

# Overview of Flight Software (FSW) Computer Software Components (CSC)

***Wide-Field Camera-specific***

Detector Control (configuration and readout)

Science Data management

Filter wheel mechanism management

Focus mechanism management

***Spectrometer-specific***

Detector Control (configuration and readout)

Science Data management

Grating wheel mechanism management

Target Acquisition – get the target into the slit

***Coronagraph-specific***

Detector Control (configuration and readout)

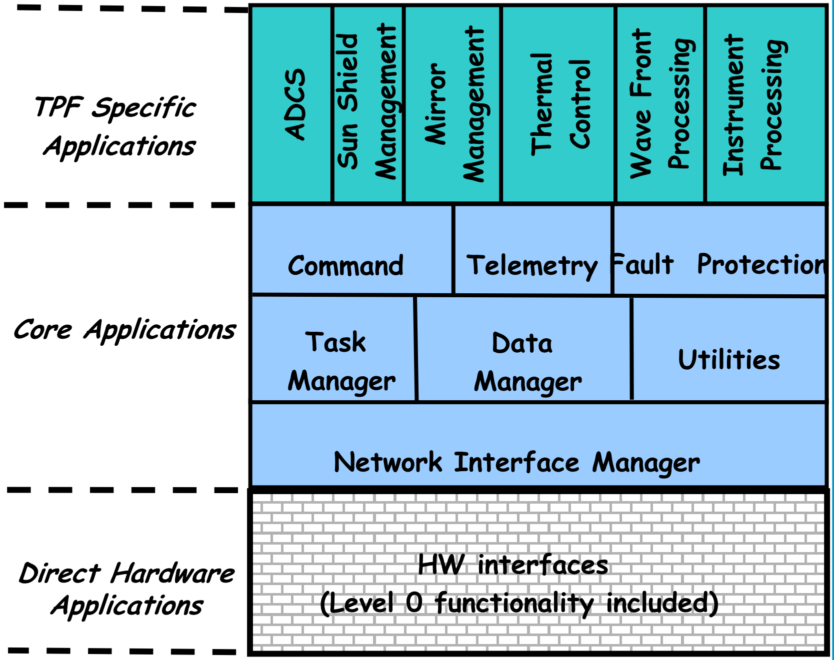
Science Data management

Pupil and Mask mechanism management

Filter wheel mechanism management

Target Acquisition – place a star behind the occulting spot

| C++ Source Lines of Code (SLOC) | |
|---|---|
| Spacecraft | 34,447 |
| Instrument | 16,644 |
| Total | 51,091 |



*TPF Specific Applications*

ADCS

Sun Shield Management

Mirror Management

Thermal Control

Wave Front Processing

Instrument Processing

*Core Applications*

Command

Telemetry

Fault Protection

Task Manager

Data Manager

Utilities

Network Interface Manager

*Direct Hardware Applications*

HW interfaces (Level 0 functionality included)

# Additional Flight Software (FSW) Computer Software Components (CSC)

ADCS (Deep Space)

Redundancy management

Subsystem configuration

Mode management

Commanding (absolute time sequences, relative time sequences, event-driven operations)

Telemetry management (including autonomous health and safety monitoring)

Thermal/heater management

Power management (solar arrays)

Propulsion and station-keeping

Telecom (DSN)

Mirror management (including segmented main mirror deployment and adjustment, management of secondary mirror, management of fine steering mirror (guider), and management of deformable mirror (actuator adjustment in response to wavefront control algorithms)

Star-tracker management, including guide-star acquisition and tracking

Momentum wheel management, and momentum dumping

Sun Shield gimbal management

High Gain Antenna gimbal management

Initial calibration and diagnosis of alignment of structures and optics(metrology)

Wavefront sensing and wavefront control

Fault Manager

Task Manager

Data Manager

Memory Manager

Network Interface Manager

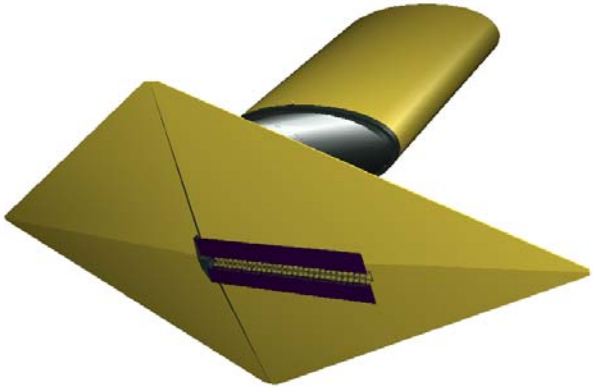
Instrument Command and Housekeeping

Management of science data

Boot-up

Board Support Package

# Overview of the Electrical Power and Distribution System (EPDS)



- Assumptions:
  - Operation at 1 AU, no eclipse
  - 10 yr design life (i.e. 1 solar cycle)
  - Technology Freeze: 2010
  - Fully Redundant Architecture
  - 50% power margin at EOL
  - Battery capable of supporting 1 hour in safe mode
- Design Overview:
  - Solar Array with 28% efficiency cells, ISS design approach
  - Three 44 A-hr Li-ion batteries
  - Redundant power electronics for charge control, array and load switching

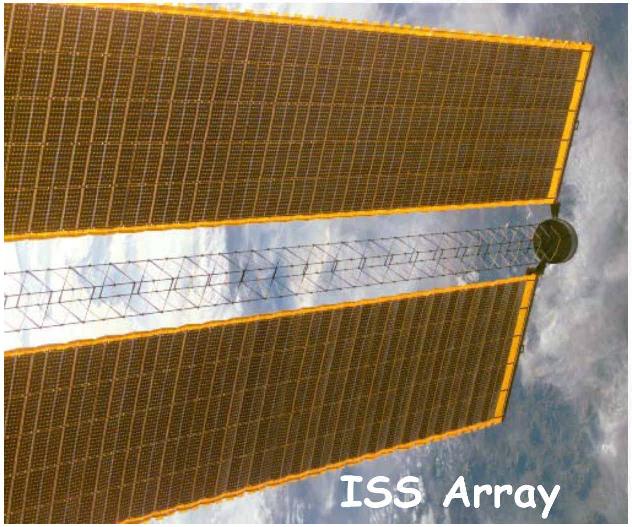
# Power Requirements Show Ample Growth Contingency and Margin

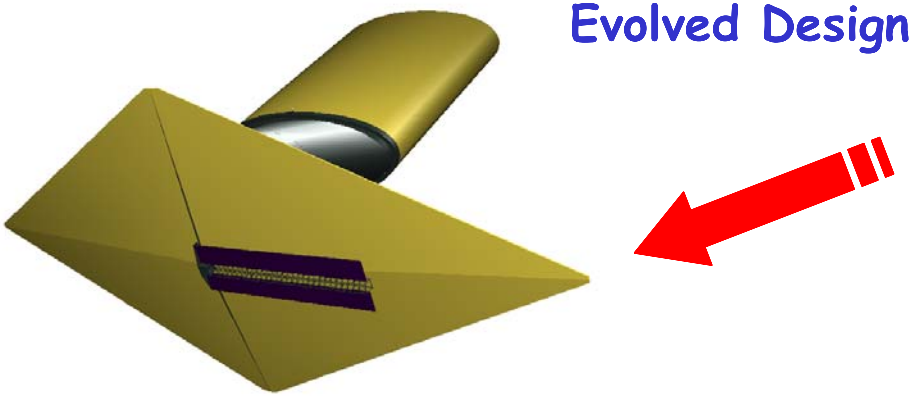
| Description | Power (W) | Science Operation | Safe Mode |
|---|---|---|---|
| Instrument | 230.0 | 230.0 | 50.0 |
| Attitude Determination and Control | 77.0 | 77.0 | 77.0 |
| Electrical Power Subsystem | 115.0 | 115.0 | 115.0 |
| Command and Data Handling | 58.0 | 58.0 | 58.0 |
| Structure | 0.0 | 0.0 | 0.0 |
| Mechanisms | 0.0 | 0.0 | 0.0 |
| Thermal Control Subsystem | 900.0 | 900.0 | 630.0 |
| Telecomm | 36.5 | 36.5 | 36.5 |
| Propulsion | 27.3 | 27.3 | 27.3 |
| Total (Current Best Estimate) | 1443.8 | 1443.8 | 993.8 |
| Growth Contingency (30%) | 433.1 | 433.1 | 298.1 |
| Margin (15%) | 281.5 | 281.5 | 193.8 |
| **TOTAL w/ 50% Growth Capability** | **2158.5** | **2158.5** | **1485.7** |

# TPF Coronagraph Solar Array

- Solar Array:
  - ISS heritage array: blanket array with boom deployment
  - 8.0 m$^2$ active cell area
  - 28% Triple-junction GaInP$_2$/GaAs/Ge solar cells, 150 $\mu$m coverglass
  - JPL91 Solar Flare radiation model (one cycle), RDM=2
  - UV, contamination, micrometeoroid, manufacturing losses
  - 2380 W BOL, 2168 W at 10 yrs
  - Total array mass = 85 kg (CBE)

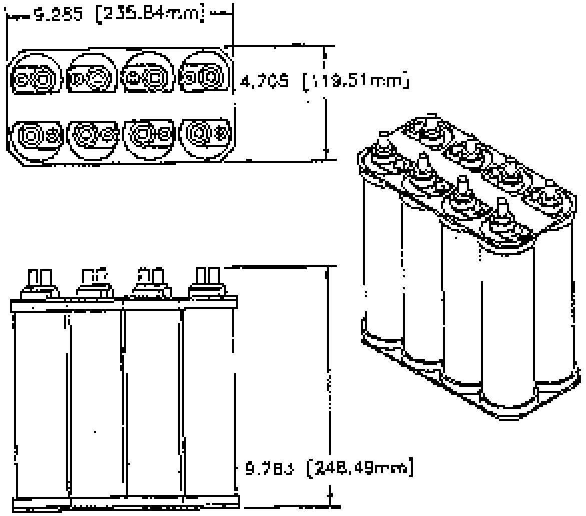

AEC-ABLE FASTmast


ISS Array


Evolved Design

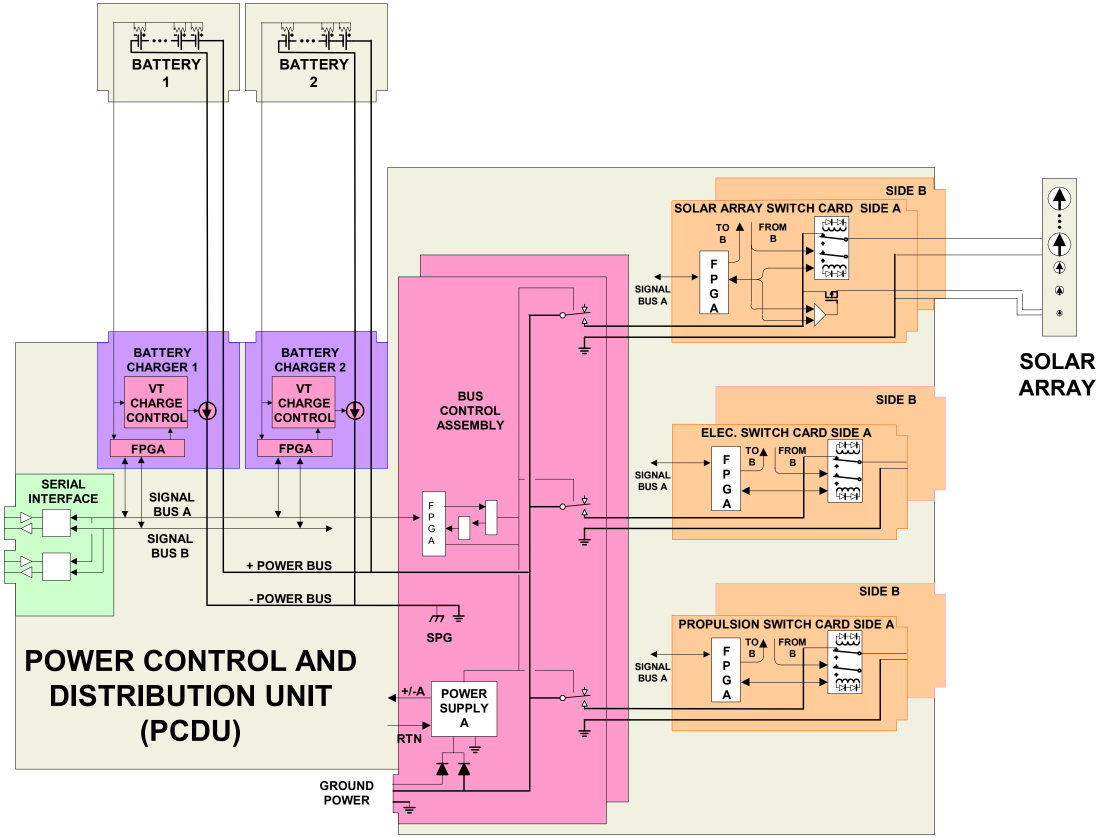
# TPF Coronagraph Batteries

- Batteries:
  - Three 44 A-hr Li-ion batteries, 8 cells in series
  - Separate thermal control within bus to mitigate calendar fade
  - Individual cell bypass and balance circuitry; overcharge protection
  - 40% DOD for 1 hr launch phase in safe mode
  - Worst-case offpointing on station approx 15 minutes
    - 10% DOD
    - 4x margin over launch



# Power Electronics

- Fully redundant charge control, array and load switching



# EPDS Technologies

- Minimal new technology in EPDS design
  - Solar array has direct ISS heritage
  - 28% Solar cells currently in qualification
  - Li-ion battery qualified; ample flight heritage by 2010
  - Power electronics has direct Deep Impact heritage
- Design allows for easy technology insertion
  - Power generation easily configured for higher efficiency cells
  - Possible integration of sunshield and solar array if advantageous
    - Thin-film cells (CIGS, $\alpha$Si) currently at TRL 2-3
    - Excess area available on sunshield to populate with thin-film solar cells on Kapton substrate
    - Would require cell and substrate validation
    - Potential mass and cost savings

# Summary of TPF Coronagraph Mass

| | Mature Mass (kg) |
|---|---|
| Optical Telescope Assembly | 1857.7 |
| Science Instruments | 1400.0 |
| Payload Electronics | 57.5 |
| Total Payload | 3315.2 |
| Structures & Mechanisms | 1392.0 |
| Electrical Power & Distribution System | 331.2 |
| Command & Data Handling System | 57.5 |
| Telecommunications | 28.5 |
| Attitude Determination & Control System | 80.6 |
| Propulsion | 81.5 |
| Dry Bus Mass | 2049.3 |
| Total Observatory Dry Mass | 5364.5 |
| Propellants & Pressurants | 609.5 |
| Total Observatory Launch Mass | 5974.0 |

# Detail TPF Coronagraph Mass & Power Estimate

| Maturity | | | | | Nominal | Nominal | Mature | Power | Active | On Orbit | Power | Power |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Grwth | | | Mass per unit | Total Mass | Total Mass | Peak | Units | Duty | Orbit Avg | Peak |
| Type | Code | (%) | Item | Qty | (kg) | (kg) | (kg) | Unit (W) | Qty | Cycle (%) | Total (W) | Total (W) |
| | | | **Payload** | | | | | | | | | |
| | | | **Optical Telescope Assy** | | **1429.00** | **1429.00** | **1857.70** | | | | **0.0** | **0.0** |
| **3** | **E** | 30 | Primary Mirror + Optical Bench + Acuators | **1** | **1099.00** | 1099.00 | 1428.70 | **0.0** | **1** | **0** | 0.0 | 0.0 |
| **3** | **E** | 30 | Secondary Mirror + Deployment Assy | **1** | **200.00** | 200.00 | 260.00 | **0.0** | **1** | **0** | 0.0 | 0.0 |
| **3** | **E** | 30 | Deformable Mirror Assy | **1** | **30.00** | 30.00 | 39.00 | **0.0** | **1** | **0** | 0.0 | 0.0 |
| **3** | **E** | 30 | Deployable Baffle | **1** | **100.00** | 100.00 | 130.00 | **0.0** | **1** | **0** | 0.0 | 0.0 |
| | | | **Integrated Science Instruments** | | **1400.00** | **1400.00** | **1400.00** | | | | **150.0** | **150.0** |
| **3** | **S** | 0 | Science Instruments | **1** | **1400.00** | 1400.00 | 1400.00 | **150.0** | **1** | **100** | 150.0 | 150.0 |
| | | | **Payload Processing Electronics** | | **40.00** | **50.00** | **57.50** | | | | **80.0** | **80.0** |
| **9** | **E** | 15 | WPU (Wavefront Processor Unit) | **2** | **10.00** | 20.00 | 23.00 | **20.0** | **1** | **100** | 20.0 | 20.0 |
| **9** | **E** | 15 | DMPCU (Deformable Mirror Power Control Unit) | **1** | **15.00** | 15.00 | 17.25 | **30.0** | **1** | **100** | 30.0 | 30.0 |
| **9** | **E** | 15 | PMPCU (Primary Mirror Power Control Unit) | **1** | **15.00** | 15.00 | 17.25 | **30.0** | **1** | **100** | 30.0 | 30.0 |
| | | **15%** | **Total Payload Mass** | | | **2879.0** | **3315.2** | | | | **230.0** | **230.0** |

Conservative Mass & Power Estimates with Growth Estimates

# Detail TPF Coronagraph Mass & Power Estimate (Cont'd)

| Maturity | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Type | Code | Grwth (%) | | Item | Qty | Nominal Mass per unit (kg) | Nominal Total Mass (kg) | Mature Total Mass (kg) | Power Peak Unit (W) | Active Units Qty | On Orbit Duty Cycle (%) | Power Orbit Avg Total (W) | Power Peak Total (W) |
| | | | | **Stuctures & Mechanisms** | | **1152.50** | **1160.00** | **1392.00** | | | | **0.0** | **0.0** |
| 1 | E | 20 | | Structure | 1 | 1050.00 | 1050.00 | 1260.00 | 0.0 | 1 | 0 | 0.0 | 0.0 |
| 1 | E | 20 | | Articulating Sun Sheild (Doesn't Include Solar Array) | 1 | 100.00 | 100.00 | 120.00 | 0.0 | 1 | 0 | 0.0 | 0.0 |
| 1 | E | 20 | | Separation Devices | 4 | 2.50 | 10.00 | 12.00 | 0.0 | 1 | 0 | 0.0 | 0.0 |
| | | | | **Electrical & Power Distribution** | | **249.00** | **249.00** | **331.17** | | | | **115.0** | **115.0** |
| 4 | E | 33 | | PI (Power Interface) | 1 | 50.00 | 50.00 | 66.50 | 70.0 | 1 | 100 | 70.0 | 70.0 |
| 4 | E | 33 | | Solar Array | 1 | 85.00 | 85.00 | 113.05 | 0.0 | 0 | 0 | 0.0 | 0.0 |
| 4 | E | 33 | | Li Ion Battery | 1 | 44.00 | 44.00 | 58.52 | 20.0 | 1 | 100 | 20.0 | 20.0 |
| 4 | E | 33 | | Electrical Cabling | 1 | 70.00 | 70.00 | 93.10 | 25.0 | 1 | 100 | 25.0 | 25.0 |
| | | | | **Command Control & Data Handling** | | **25.00** | **50.00** | **57.50** | | | | **58.0** | **58.0** |
| 9 | E | 15 | | SCU (Spacecraft Control Unit) | 2 | 10.00 | 20.00 | 23.00 | 20.0 | 1 | 100 | 20.0 | 20.0 |
| 9 | E | 15 | | RIU (Remote Interface Unit) | 2 | 15.00 | 30.00 | 34.50 | 38.0 | 1 | 100 | 38.0 | 38.0 |

Conservative Mass & Power Estimates with Growth Estimates

# Detail TPF Coronagraph Mass & Power Estimate (Cont'd)

| Maturity | | | | | Nominal | Nominal | Mature | Power | Active | On Orbit | Power | Power |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Grwth | | | Mass per unit | Total Mass | Total Mass | Peak | Units | Duty | Orbit Avg | Peak |
| Type | Code | (%) | Item | Qty | (kg) | (kg) | (kg) | Unit (W) | Qty | Cycle (%) | Total (W) | Total (W) |
| | | | **Telecommunications** | | **16.92** | **24.76** | **28.47** | | | | **186.6** | **186.6** |
| 9 | E | 15 | SDST w/ Ka-band | 2 | 3.00 | 6.00 | 6.90 | 15.8 | 2 | 100 | 31.6 | 31.6 |
| 9 | E | 15 | HGA - 0.56 meter, 55% efficiency, Ka-band | 1 | 0.60 | 0.60 | 0.69 | 0.0 | 0 | 0 | 0.0 | 0.0 |
| 9 | E | 15 | MGA - 16 dBi, X-band | 1 | 0.48 | 0.48 | 0.55 | 0.0 | 0 | 0 | 0.0 | 0.0 |
| 9 | E | 15 | LGA -Tx | 2 | 0.12 | 0.24 | 0.28 | 0.0 | 0 | 0 | 0.0 | 0.0 |
| 9 | E | 15 | LGA -Rx | 2 | 0.12 | 0.24 | 0.28 | 0.0 | 0 | 0 | 0.0 | 0.0 |
| 9 | E | 15 | 60 Watt Ka-band TWTA | 2 | 3.10 | 6.20 | 7.13 | 100.0 | 1 | 100 | 100.0 | 100.0 |
| 9 | E | 15 | 15 Watt X-band SSPA | 2 | 1.50 | 3.00 | 3.45 | 55.0 | 1 | 100 | 55.0 | 55.0 |
| 9 | E | 15 | Misc Components (X and Ka BPFs, X and Ka Couplers, switches, notch filters, waveguide, coax) | 1 | 8.00 | 8.00 | 9.20 | 0.0 | 0 | 0 | 0.0 | 0.0 |
| | | | **Thermal Control** | | **60.00** | **60.00** | **78.00** | | | | **900.0** | **1000.0** |
| 5 | E | 30 | Blankets, Shielding, Tapes, etc | 1 | 40.00 | 40.00 | 52.00 | 0.0 | 0 | 0 | 0.0 | 0.0 |
| 5 | E | 30 | Heaters | 1 | 10.00 | 10.00 | 13.00 | 500.0 | 1 | 80 | 400.0 | 500.0 |
| 5 | E | 30 | Optical Bench Heaters | 1 | 10.00 | 10.00 | 13.00 | 500.0 | 1 | 100 | 500.0 | 500.0 |

Conservative Mass & Power Estimates with Growth Estimates

# Detail TPF Coronagraph Mass & Power Estimate (Cont'd)

| Maturity | | | | | Nominal | Nominal | Mature | Power | Active | On Orbit | Power | Power |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Grwth | | | Mass per unit | Total Mass | Total Mass | Peak | Units | Duty | Orbit Avg | Peak |
| Type | Code | (%) | Item | Qty | (kg) | (kg) | (kg) | Unit (W) | Qty | Cycle (%) | Total (W) | Total (W) |
| | | | **Attitude Determination & Control** | | **22.31** | **70.12** | **80.64** | | | | **77.0** | **189.0** |
| 6 | E | 15 | Star Tracker | 2 | 3.00 | 6.00 | 6.90 | 9.0 | 2 | 100 | 18.0 | 18.0 |
| 6 | E | 15 | SIRU | 2 | 6.60 | 13.20 | 15.18 | 31.0 | 1 | 100 | 31.0 | 31.0 |
| 6 | E | 15 | Reaction Wheels | 4 | 7.70 | 30.80 | 35.42 | 35.0 | 4 | 20 | 28.0 | 140.0 |
| 6 | E | 15 | Reaction Wheels Isolation System | 4 | 5.00 | 20.00 | 23.00 | 0.0 | 0 | 0 | 0.0 | 0.0 |
| 6 | E | 15 | Course Sun Sensor | 12 | 0.01 | 0.12 | 0.14 | 0.0 | 0 | 0 | 0.0 | 0.0 |
| | | | | | | | | | | | | |
| | | | **Propulsion** | | **65.94** | **71.64** | **81.52** | | | | **27.3** | **125.0** |
| 6 | K | 2 | 4N RCS Thruster | 12 | 0.36 | 4.32 | 4.41 | 105.0 | 1 | 25 | 26.3 | 105.0 |
| 6 | K | 2 | 22N RCS Thruster | 4 | 0.58 | 2.32 | 2.37 | 0.0 | 1 | 10 | 0.0 | 0.0 |
| 6 | E | 15 | N2H4 Tank | 1 | 40.00 | 40.00 | 46.00 | 0.0 | 0 | 0 | 0.0 | 0.0 |
| 6 | E | 15 | Pressurant Tank | 1 | 5.00 | 5.00 | 5.75 | 0.0 | 0 | 0 | 0.0 | 0.0 |
| 6 | E | 15 | Manifold (Lines & Fittings) | 1 | 15.00 | 15.00 | 17.25 | 0.0 | 0 | 0 | 0.0 | 0.0 |
| 6 | E | 15 | Valves, Sensors, etc | 1 | 5.00 | 5.00 | 5.75 | 20.0 | 1 | 5 | 1.0 | 20.0 |
| | | | | | | | | | | | | |
| | | **22%** | **Total Bus Dry Mass** | | | **1685.5** | **2049.3** | | | | **1364** | **1674** |
| | | | | | | | | | | | | |
| | | **18%** | **Total Spacecraft Dry Mass** | | | **4564.5** | **5364.5** | | | | **1594** | **1904** |
| | | | | | | | | | | | | |
| | | | **Propellants & Pressurants** | | **510.00** | **530.00** | **609.50** | | | | | |
| 6 | E | 15 | N2H4 (Hydrazine) | 1 | 490.00 | 490.00 | 563.50 | | | | | |
| 6 | E | 15 | Pressurant (Nitrogen) | 2 | 20.00 | 40.00 | 46.00 | | | | | |
| | | | | | | | | | | | | |
| | | **17%** | **Total Spacecraft Launch Mass** | | | **5094.5** | **5974.0** | | | | **1594** | **1904** |

Conservative Mass & Power Estimates with Growth Estimates

# Detail TPF Coronagraph Mass & Power Estimate (Cont'd)

| Maturity | | | | | | Nominal | Nominal | Mature |
|---|---|---|---|---|---|---|---|---|
| | | Grwth | | | | Mass per unit | Total Mass | Total Mass |
| Type | Code | (%) | | Item | Qty | (kg) | (kg) | (kg) |
| | | | | **Atlas V (551) Performance** | | | | **6300.00** |
| **6** | **S** | 0 | | Vehicle performance to C3 = 0.3 km2/sec2 | | | | 6300.00 |
| **1** | **E** | 20 | | Special Launch Adapters | | **0.00** | 0.00 | 0.00 |
| | | **5%** | | **Atlas V (551) Launch Margin** | | | | **326.0** |
| | | | | **Delta IV (4050H-19) Performance** | | | | **9255.00** |
| **6** | **S** | 0 | | Vehicle performance to C3 = 0.3 km2/sec2 | | | | 9255.00 |
| **1** | **E** | 20 | | Special Launch Adapters | | **0.00** | 0.00 | 0.00 |
| | | **35%** | | **Delta IV (4050H-19) Launch Margin** | | | | **3281.0** |

Large Launch Margin For Delta IV Heavy

# TPF Coronagraph Reliability & Robustness

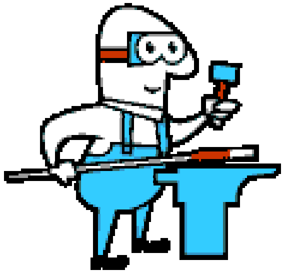
- Spacecraft (Bus)

  Designed for High Reliability
    - Dual String Approach
    - Geo Com Sats typically designed for 15 year life
- Optical Telescope Assembly (The hard part)

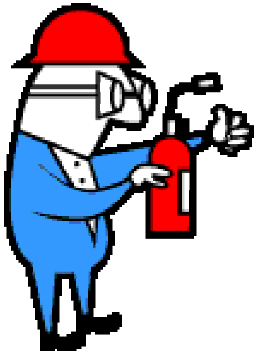
  Life ( & Extended Life) Testing will be essential to validating reliability of wavefront control mechanisms
    - Deformable Mirror
      - Analysis of failed acuators in redundant arrays of acuators
      - Design failed mode of acuators for non interference with operational acuators
    - Acuators for Primary & Secondary Mirrors
      - Analysis of failed acuators in redundant arrays of acuators
      - Design failed mode of acuators for non interference with operational acuators
    - Fine Steering Mirror
      - Use High Heritage Designs

  Optical Contamination over 5 to 10 year life
    - Observatory flown in very benign environment

# Section 8:
# Integration and Test



## Kenny Epstein



I & T Approach
and
Integrated Test Approach

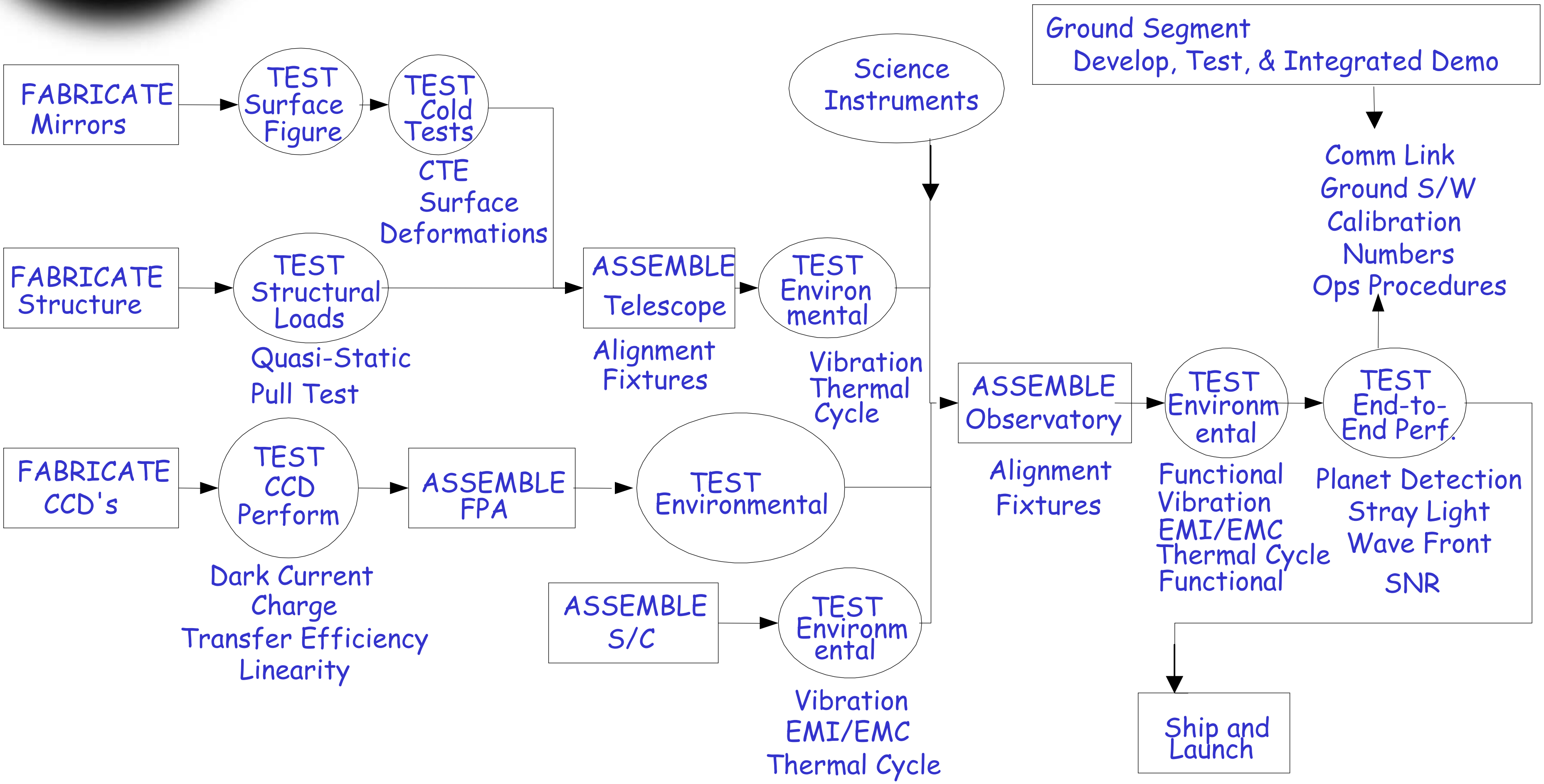
# Integration & Test Overview

- Careful planning key to timely integrating & testing of this large system
  - Minimize time in chamber (tailor the environmental tests)
  - Reserve system-level testing for verification tests only
  - Identify optical system testing approaches early
  - Use of Robust Software & Hardware Test Benches will be essential
- Facility selection for final I&T
  - Defining optical test approach will determine test facility requirements
  - Several government facilities capable of supporting TPF final I&T needs
- Transportation is a consideration but not a major driver
  - Impacts testing methodology
  - Minimally effects I&T facility selection

# Standard Test Strategies for Our Spacecraft

- We will maximize design verification through test
  - Other verification methods (analysis, simulation, etc) used for requirements not verifiable through ground test
- We verify performance at lowest possible level and then re-verify at higher assembly level
- We perform Test Design Reviews for all tests
  - Peer review of test procedures and GSE design
    - Includes inputs from systems, design, materials and processes, and contamination control engineering
- We perform a Critical Process Review (CPR) prior to each test
  - Ready-to-test meeting involving customer, management, engineering, quality, and technicians
  - Ensures test readiness and article configuration
- We follow a "Test like you fly, fly like you test" philosophy with high fidelity, realistic tests and test equipment

# TPF Coronagraph Integration and Test Flow



FABRICATE Mirrors → TEST Surface Figure → TEST Cold Tests

CTE
Surface Deformations

FABRICATE Structure → TEST Structural Loads

Quasi-Static
Pull Test

→ ASSEMBLE Telescope → TEST Environmental

Alignment Fixtures

Vibration
Thermal Cycle

FABRICATE CCD's → TEST CCD Perform → ASSEMBLE FPA → TEST Environmental

Dark Current
Charge Transfer Efficiency
Linearity

ASSEMBLE S/C → TEST Environmental

Vibration
EMI/EMC
Thermal Cycle

Science Instruments

→ ASSEMBLE Observatory → TEST Environmental → TEST End-to-End Perf. → Ship and Launch

Alignment Fixtures

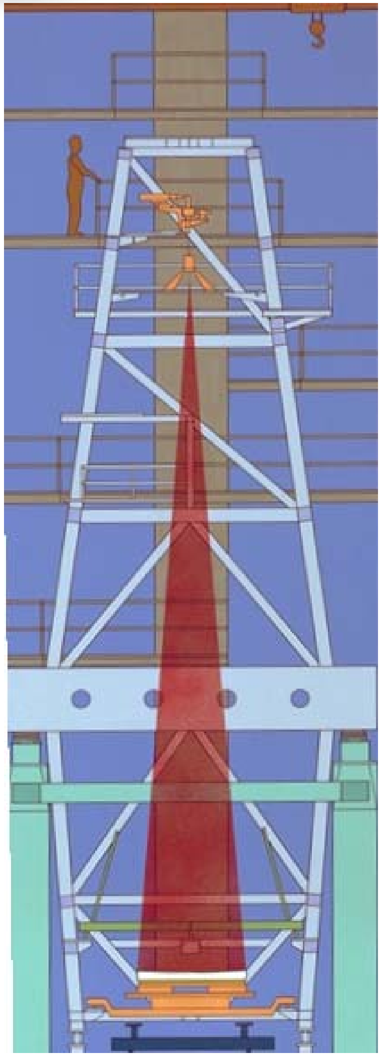
Functional
Vibration
EMI/EMC
Thermal Cycle
Functional

Planet Detection
Stray Light
Wave Front
SNR

Ground Segment
Develop, Test, & Integrated Demo

Comm Link
Ground S/W
Calibration Numbers
Ops Procedures

# TPF Coronagraph Primary Mirror Test



AOSD Segmented Primary Mirror Test

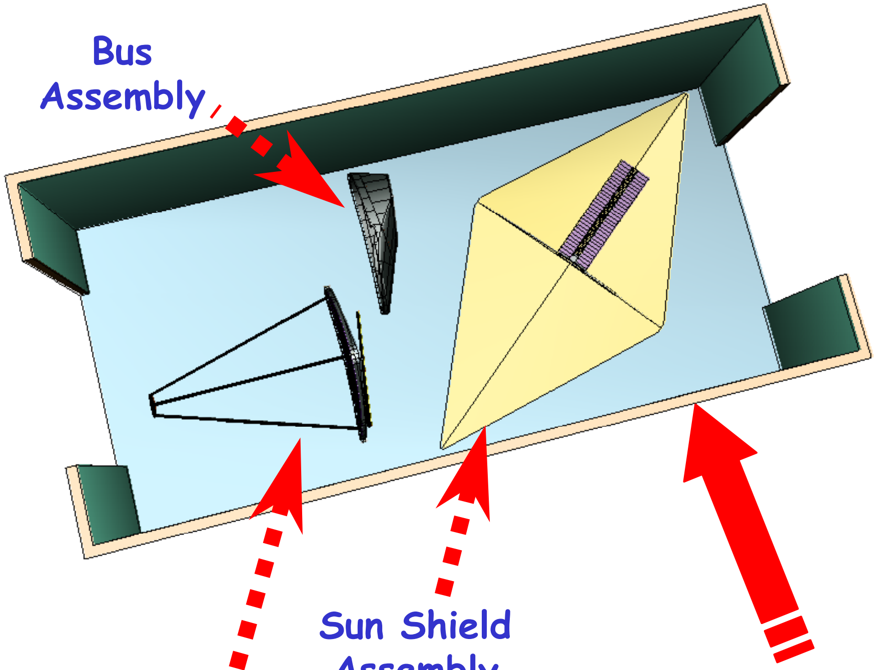
Kodak and Ball will draw on large system test experience to provide PM test for TPF

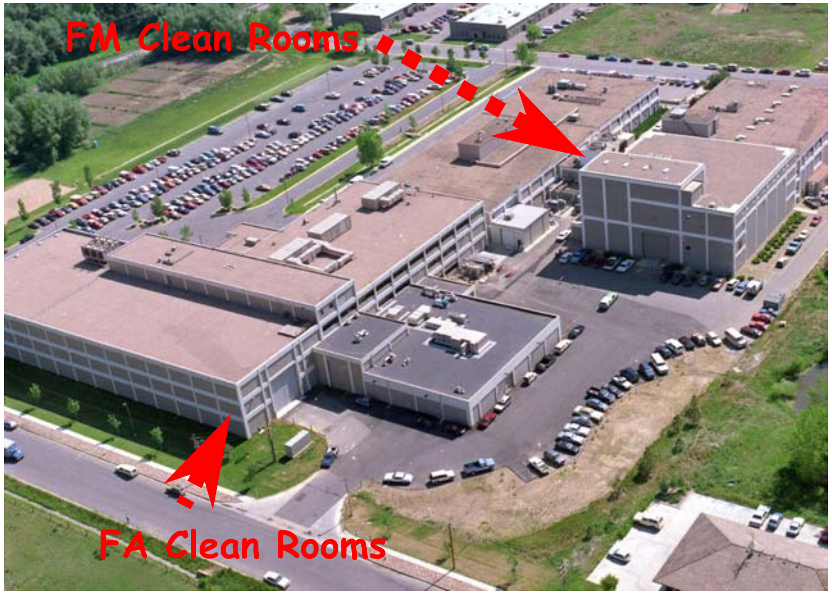
PM test will require expanded facilities at Kodak or use of existing government facilities

TAKE PICTURES. FURTHER.

# TPF Coronagraph Assembly & Integration Overview

- Final Assembly & System Checkout in the FA-1 Clean Room
  - Class 100,000 (10,000 Tented Areas)
  - Program Heritage -NGST Optical Test Facility
- Optical Telescope Assembly & Subsystem Tests in FM Clean Room
  - Class 10,000 or 1,000 Rooms Available
  - Program Heritage – Hubble Instruments (COSTAR, WFC, NICMOS, STIS)





# Several Acoustic Test Facilities Are Available to Qualify TPF Stowed

<u>GSFC Greenbelt, MD</u>

Size:
- 10 m X 8.2 m X 12.8 m

Door:
- 4.5 m X 9.4 m

Crane:
- 6,800 kg

Max SPL:
- 150 db overall

Acoustic Power:
- 3-10 kW

Frequency range:
- 25 Hz to 10 kHz

Cleanliness:
- 100,000 capable

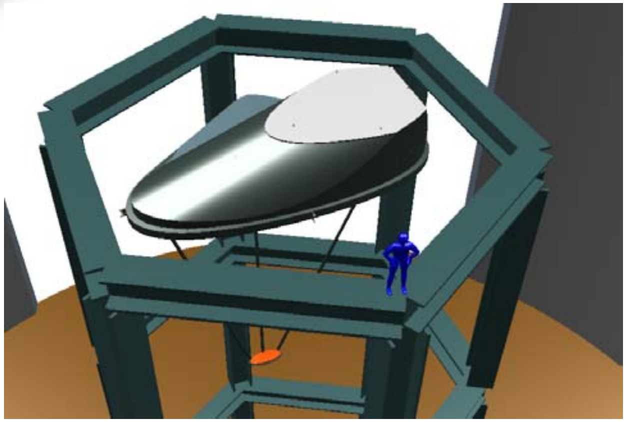
<u>Lockheed Martin, Sunnyvale, CA</u>

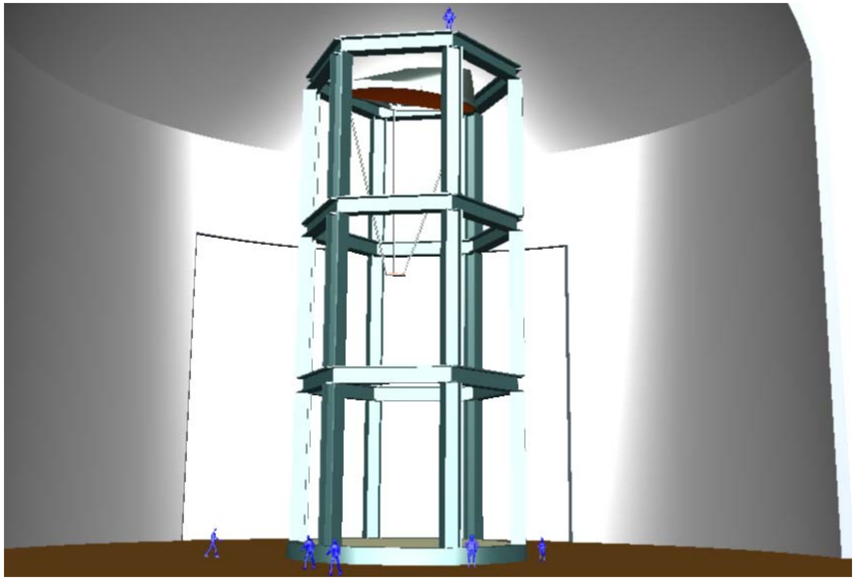
- Size:
  - 13.4 m X 15.2 m X 26.2 m
- Door:
  - 7.9 m X 25.6 m
- Crane:
  - 18,144 kg
- Acoustic Power:
  - 250 kW
- Low Freq Cutoff:
  - 20 Hz
- Cleanliness:
  - 300,000

<u>Boeing, Kent, WA</u>

- Size:
  - 7.3 m x 8.5 m x 17.7 m
- Door:
  - 5.8 m x 12.8 m
- Crane:
  - 1,814 kg
- Door Bridge:
  - 9,072 kg
- Sound Level:
  - 155 dB OA SPL
- Low Freq Cutoff:
  - 20 Hz
- Cleanliness:
  - 100,000

# Observatory Ground Test Overview (Integrated System Test)





- Several Facilities to choose from
  - AEDC Mark I $\phi$12.8m x 25m
  - GRC SPF $\phi$30.5m x 37.2m
  - Johnson A $\phi$16.8m x 27.4m
- Test Set up Evaluated for Plum Brook Space Power Facility
  - Largest Facility
  - Very Low vibration level
  - NASA controlled facility
- Test the Entire Observatory
  - Only the Sunshield & Array Removed for Testing
  - Vertical orientation eliminates moments into primary aperture
  - Vacuum Test at on orbit thermal environment

# Coronagraph Observatory Performance -- Idealized Test Concept

- The most demanding test objective is to verify end-to-end system performance prior to launch; ideally this would involve:
  - Test in operational environment -- monitor structure & surface deformation
  - Design a scene generator which simulates a terrestrial planet and its star, thus having a total brightness ratio of $10^{10}$, and produces a full-aperture collimated signal beam with exozodi and proper angular separations
  - The test will require the observatory to report data convincing enough to permit a claim of detecting the "planet"
  - Ground software will b e exercised to extract, identify, and characterize the planet signal
  - Tests against simulated astrophysics target signals may also be required
- The above ideal performance test probably cannot be fully implemented and may have to be partially replaced by WFE measurements & modeling

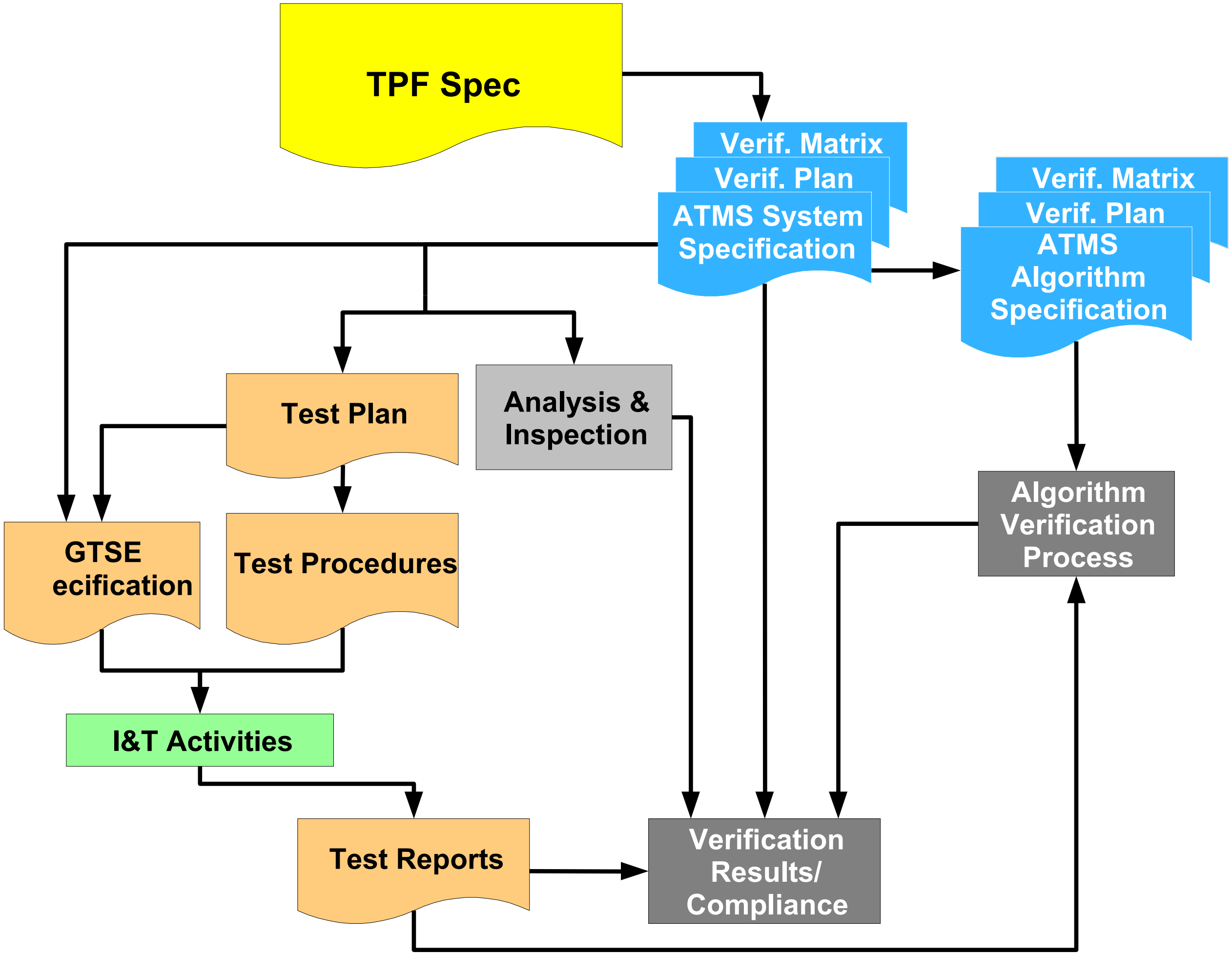
# Test Equipment Challenges

- The challenges for the test equipment are two-fold:
  - The primary mirror and hence the Spacecraft are very large
  - The accuracy requirements are state of the art
  - Alignment tolerances will need to be examined
    - within Theodilites, Axyz system, Interferometer performance specs?
  - Spacecraft GSE will use existing STOC (S/C Test Operations Console) design
  - Instrument GSE will use existing ITOC (Instrument Test Operations Console) design
  - Planet detection simulator design will be significant challenge
    - leverage off GSE from Kepler ?

# *Additional Integration & Test Background Material*

# Verifications Methods Planned for TPF

- We flow down verification requirements from POS to System Specification
- Our Verification and Test Plans identify required I&T activities
- Our GTSE Specifications and Test Procedures are developed based upon plans
- We will write test reports to document test activities and report results for compliance to verification requirements
- Our integration and test processes are ISO certified



TPF Spec

Verif. Matrix
Verif. Plan
ATMS System Specification

Verif. Matrix
Verif. Plan
ATMS Algorithm Specification

Test Plan

Analysis & Inspection

Algorithm Verification Process

GTSE ecification

Test Procedures

I&T Activities

Test Reports

Verification Results/ Compliance

# Example of Requirements Traceability

- We use DOORS to sort test requirements, link requirements to test procedures, and track requirement verifications

| Object Number | TPF System Spec | Compliance Criteria | N/A | T | D | A | S | I | EDU | Proto Flight | FM | Section 4 reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.2.1.8.3 | **3.2.1.8.3 Beam Efficiency** | | X | | | | | | | | | |
| 3.2.1.8.3.0-1 | The antenna beam efficiency shall be 95% or better. | | | X | | | | | X | X | X | 4.2.15.7 |
| 3.2.1.8.3.0-2 | Beam efficiency shall be met at all frequencies and all beam positions. NOTE: For the purpose of this specification, beam efficiency is defined as the ratio of the power received within the "main lobe" to that of the total power received by the antenna. The "main lobe" is defined as equal to 2.5 times the HPBW. In determining the beam efficiency, the antenna is assumed to be in a radiometrically isotropic environment, i.e., the brightness temperature is the same from every direction. | | | X | | | | | X | X | X | 4.2.15.8 |

System Specification Text

Pass/fail criteria

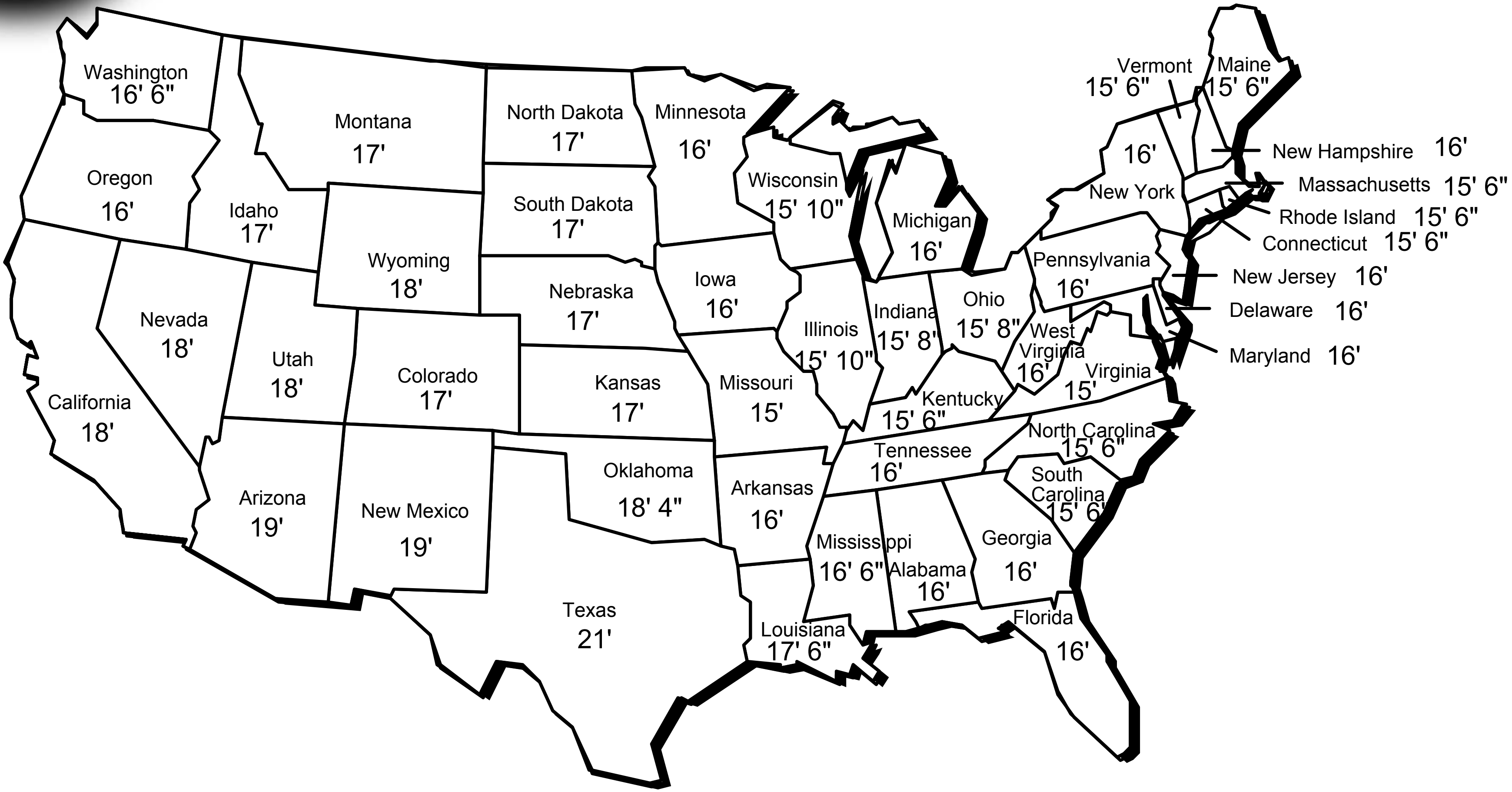
System Specification Reference Number

<u>Verification Method</u>
N/A = Not Applicable
T = Test
D = Demonstration
A= Analysis
S = Similarity
I = Inspection

Verification Applicability (Verifications are EDU, Proto-flight and Flight dependent)

System Specification Test Reference

# *Ground Transportation Height Restrictions By State*



Ground Transportation Height Restrictions May Vary Daily Due to Construction Projects

# Transportation Method Trade

| Location | Ball<br>Boulder, CO | Boeing<br>Seattle, WA | Lockheed Martin<br>Sunnyvale, CA | GSFC<br>Greenbelt, MD | JSC<br>Houston, TX |
|---|---|---|---|---|---|
| Method | | | | | |
| Ground | 4.88 m to FL | 4.88 m to FL | 4.88 m to FL | 4.75 m to FL | 4.88 m to FL |
| Air (C-5) | Peterson AFB<br>Buckley AFB | Boeing Kent, WA | Lockheed Sunnyvale, CA | Andrews AFB | JSC |
| Barge | Transport to Galveston, TX Gulf | Seattle, WA Panama / Cape Horn | Transport to San Francisco, CA<br>Panama / Cape Horn | Transport to Baltimore, MD<br>Atlantic | Transport to Galveston, TX<br>Gulf |

- Ground Transportation options limited to approximately 4.88m
  - May be increased slightly by custom low boy transport
  - Generally comes into play with all options
- Barge transportation will impact Integration decisions
- C-5, C-17, Antonov transport opens up most integration site options