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Space & Electronics

TPF Final Presentation

December 12, 2001

Agenda

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• Introduction	10 minutes	Charles Lillie
• System Engineering	20 minutes	Stewart Moses
• Observatory Configuration	30 minutes	Keith Kroening
• Optical Telescope	15 minutes	Martin Flannery
• Science Instrument Module	15 minutes	Suzanne Casement
• Science Performance	30 minutes	Casement/Wright
• Break	15 minutes	
• Fabrication, Assembly and Test	10 minutes	Charles Atkinson
• Launch and Commissioning	10 minutes	Stewart Moses
• Mission Operations	10 minutes	Suzanne Casement
• Technology Roadmap	45 minutes	Lillie/Trauger
• LCC Estimate	15 minutes	Charles Lillie
• Summary	15 minutes	Charles Lillie
• Discussion	15 minutes	All

Introduction

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Study Overview

- This presentation summarizes the results of the second phase of a 21-month, ~$1.8M Mission Architecture Study for a Terrestrial Planet Finder mission, that will:
  - **Detect and characterize** the properties of **Earth-like planets** in the habitable zones around ~150 solar type stars
  - Carry out a program of **comparative planetology** in a large number of solar systems, studying gas giant and terrestrial planets, and debris disks
  - Collect important new data on targets of **general astrophysics** interest
- Last year, during Phase 1, we developed mission architectures for TPF (and explored several variants) that:
  - Met the science requirements
  - Were consistent with the mission schedule (launch in 2014)
  - Could be implemented at a reasonable cost
- This year, during Phase 2, we performed a detailed study of one potential architecture for TPF: An IR Coronagraph

Five Architecture Classes Investigated During Phase 1

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1. **Nulling Interferometer** (IR)
   - Oasis 1-3-3-1 with 4-meter apertures, cryogenic operation
   - 70-meter class baseline
2. Large Aperture **IR Coronagraph** (visible possible)
   - ~30-meter diameter primary with excellent mid-frequency figure
   - Cryogenic operation using NGST optics and cooling technology
   - Coronagraph with deformable optics, Lyot stop and apodized occulting spot
3. **Fresnel** IR Coronagraph (visible possible)
   - ~30-meter Fresnel lens primary
   - ‘Eyepiece’ satellite formation flown at distance of 6 km
   - 1.5-meter optics, Fresnel correction lenses, Lyot and coronagraph spots
4. **Sparse Aperture** (IR)
   - ~100-meter primary with ~100 subapertures (2-4 m), random positions
   - ‘Eyepiece’ satellite formation flown at 500 meters
5. **Free Flying Occulter** (visible)
   - ~70-meter apodized occulter formation flown 100,000 km away
   - 8-meter primary diffraction limited in the visible

TPF Trade Space Is Vast

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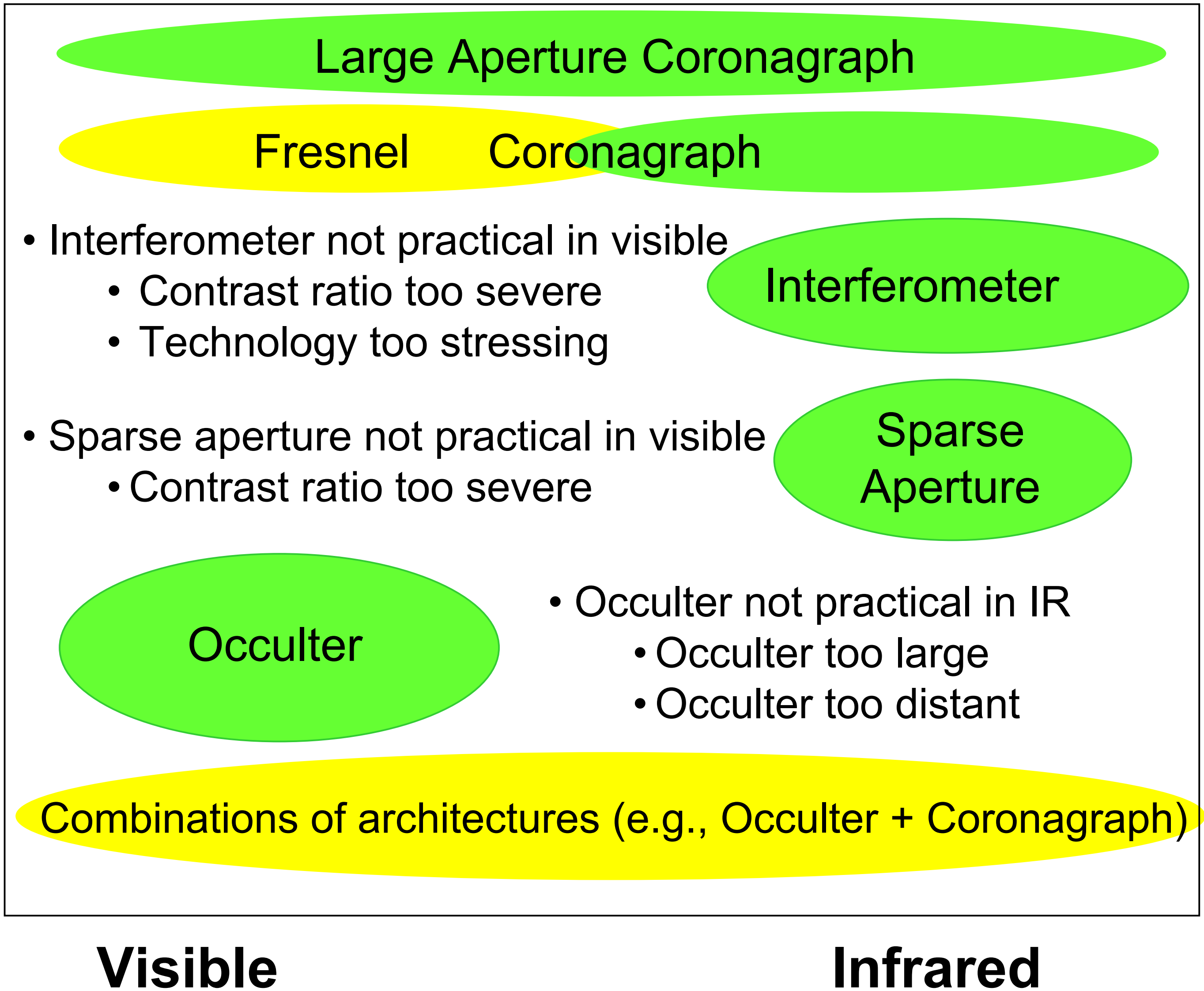
Detailed study

Evaluated, but not studied in detail



Direct Imagers Provide Greatest System Utility per Dollar

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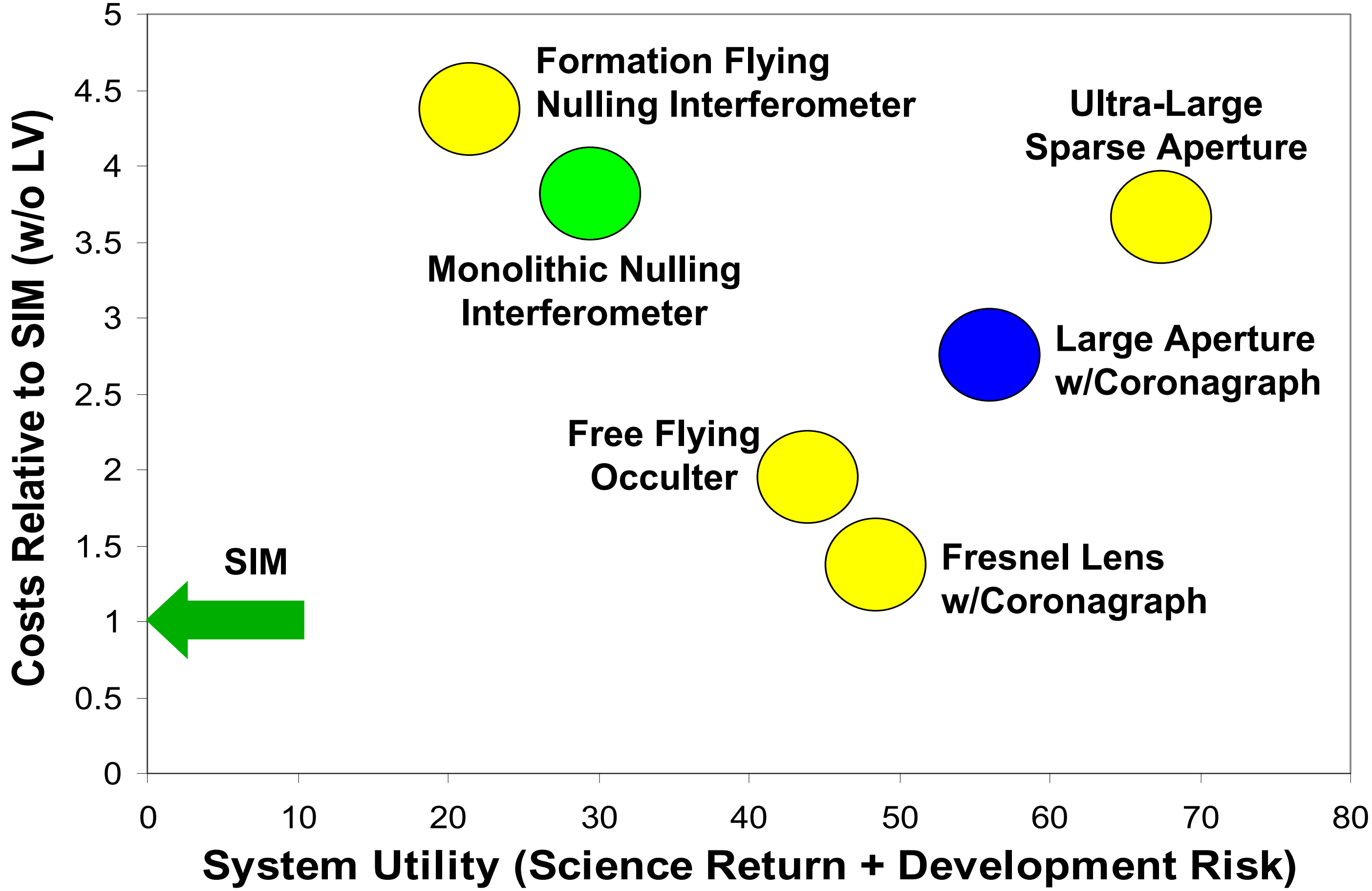
Architecture Overall Comparisons



[See Phase 1 review package for details of this analysis]

Phase 1 Study Summary

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- TRW team performed objective trades on architectures applicable to TPF mission (all concepts are very challenging)
- We normalized planet detection/characterization across all architectures, then assessed them per the JPL evaluation criteria
  - Technology, cost, risk, reliability/robustness, astrophysics, legacy
- All five architectures fall into two classes:
  - **Direct Imagers**: Simultaneous coverage of u-v plane (telescopes)
  - **Synthetic Imagers**: Sequential coverage of u-v plane (interferometers)
- We found Direct Imagers (DI) have advantages over Synthetic Imagers (SI), given normalized detection/characterization performance, since:
  - DIs have higher general astronomy utility and SIs are more specialized
  - Technical complexity of SI is more daunting on many fronts than the large system sizes required for DIs
  - Legacy of SI to future missions (LifeFinder, Planet Imager) is not clear

IR Coronagraph Design Concept

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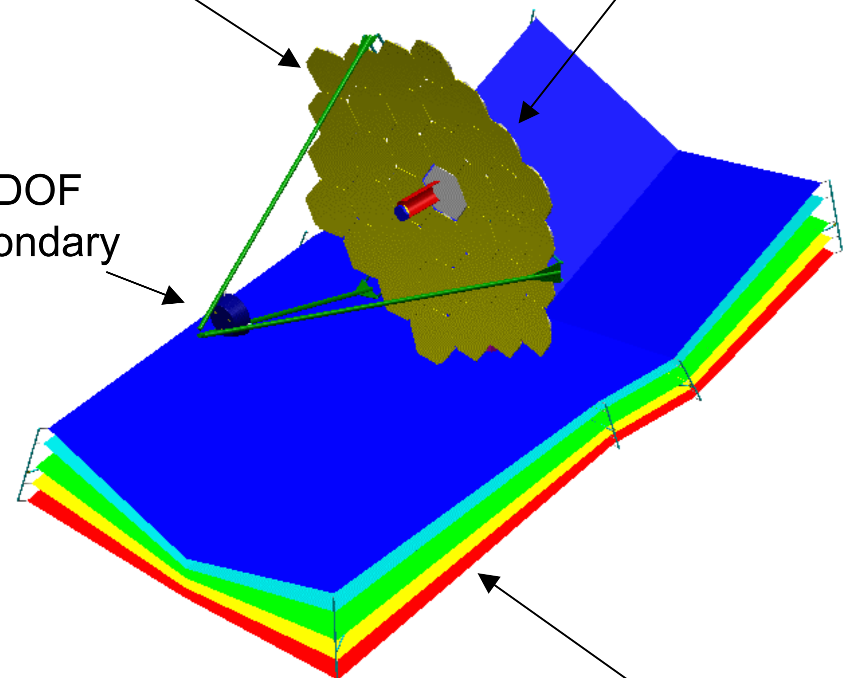
- 28-meter filled aperture telescope
  - Three-mirror anastigmat
  - 36 segments, 4-meter flat-flat
  - Composite replica optics
  - Gold mirror coatings
- Multi-layer sunshade
  - Passive cooling to ~30K
- IR Coronagraph for planetary detection/characterization
  - 10^7 contrast at 100 mas
- IR camera and spectrograph for general imaging/spectroscopy
  - 2 x 2 arcmin FOV
- Launched with EELV heavy to L2
  - On-orbit assembly option



Science Requirements

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Our IR Coronagraph meets or exceeds the science requirements for a TPF mission (in 5 years)

Obs	Parameter	Requirement	Goal	Capability
General	Sky Coverage	60%	90%	100%
	Mission Duration (years)	5	10	10
	Nominal planet defined as solid body with Earth radius, at 1 au, Temp = 270K			Comply
	Mission split 50:50 planet detection/characterization vs general imaging and sepctroscopy			Comply
Planet Detec./Charac.	Number of stars (F5-K5) surveyed (R=3, SNR=5)	150	500	150
	Number of scans for CO_2/H_20 (R=20, SNR=10)	5	25	25
	Number of scans for ozone/strong CH_4 (R=20, SNR=25)	5	25	5
	Spectral band (microns)	7 to 17	3 to 23	3 to 28
	Spectral Resolution	20	100	20
	Minimum distance of ozone detection (parsecs)	10	20	20
	Minimum distance of planet detection (parsecs)	3	2	1.3
	Point source sensitivity: 5σ, 2 hr at 12 μm, R=3 (μJy)	0.3	0.1	0.3
	Exo-zodiacal dust [density]	solar	10x solar	10x solar
	Follow-up surveys (high spectral res) uniformly distributed throughout initial survey volume			Comply
High Res. Imaging	Imaged objects for 5 year mission	800	1600	1600
	Resolution at 3 microns (millarcsecond)	0.75	0.75	N/A
	Band (microns)	3 to 17	2 to 40	3 to 28
	Spectral resolution	3 to 300	3 to 1000	3 to 300
	Spectral resolution in specified lines (FTS mode)		10^5 at 3-20 μm	N/A
	Ability to use guide star within radius: (arcseconds)	On-axis	120	600
	Dynamic range in (reconstructed) image	50:1	100:1	500:1

Advantages of IR Coronagraphy

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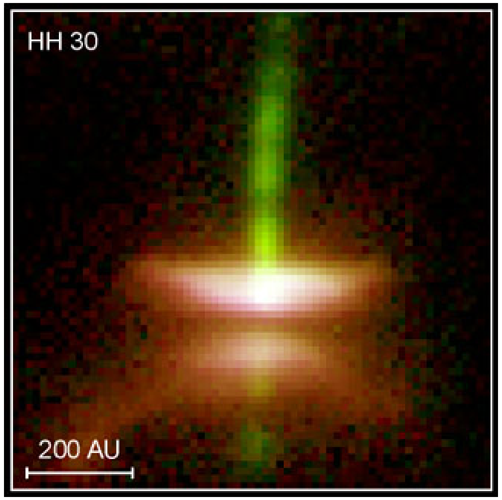
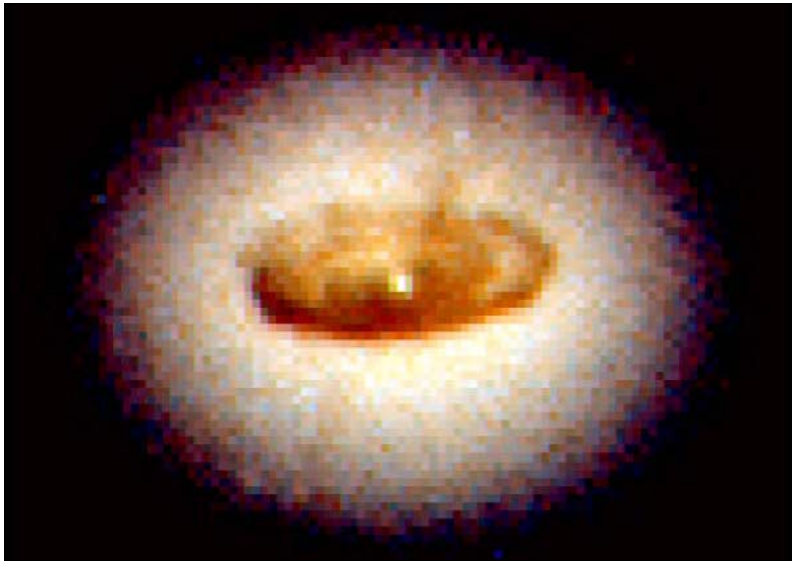
- Permits high contrast imaging within 50 mas of central star
  - 10^7 contrast in the infrared
- Provides 2-D image, without the need for reconstruction
  - Captures direct images of extrasolar planetary systems replete with multiple planets and zodiacal dust structures
  - Higher SNR possible since only a few pixels contribute to background
- Powerful tool for imaging and spectroscopy of other astrophysical objects, (with and without occulting spot) including:
  - Disks and jets in active galactic nuclei
  - Disks and outflows around protostars
  - Dark energy – supernovae
  - First objects in the universe
  - Spectroscopy of faint SIRTF and NGST discoveries
- Success in the eyes of the public rests on the powerful symbolism that only images provide

Significant Astrophysics Capabilities TRW

Spectroscopy of Faint Galaxies



Disks Around Protostars

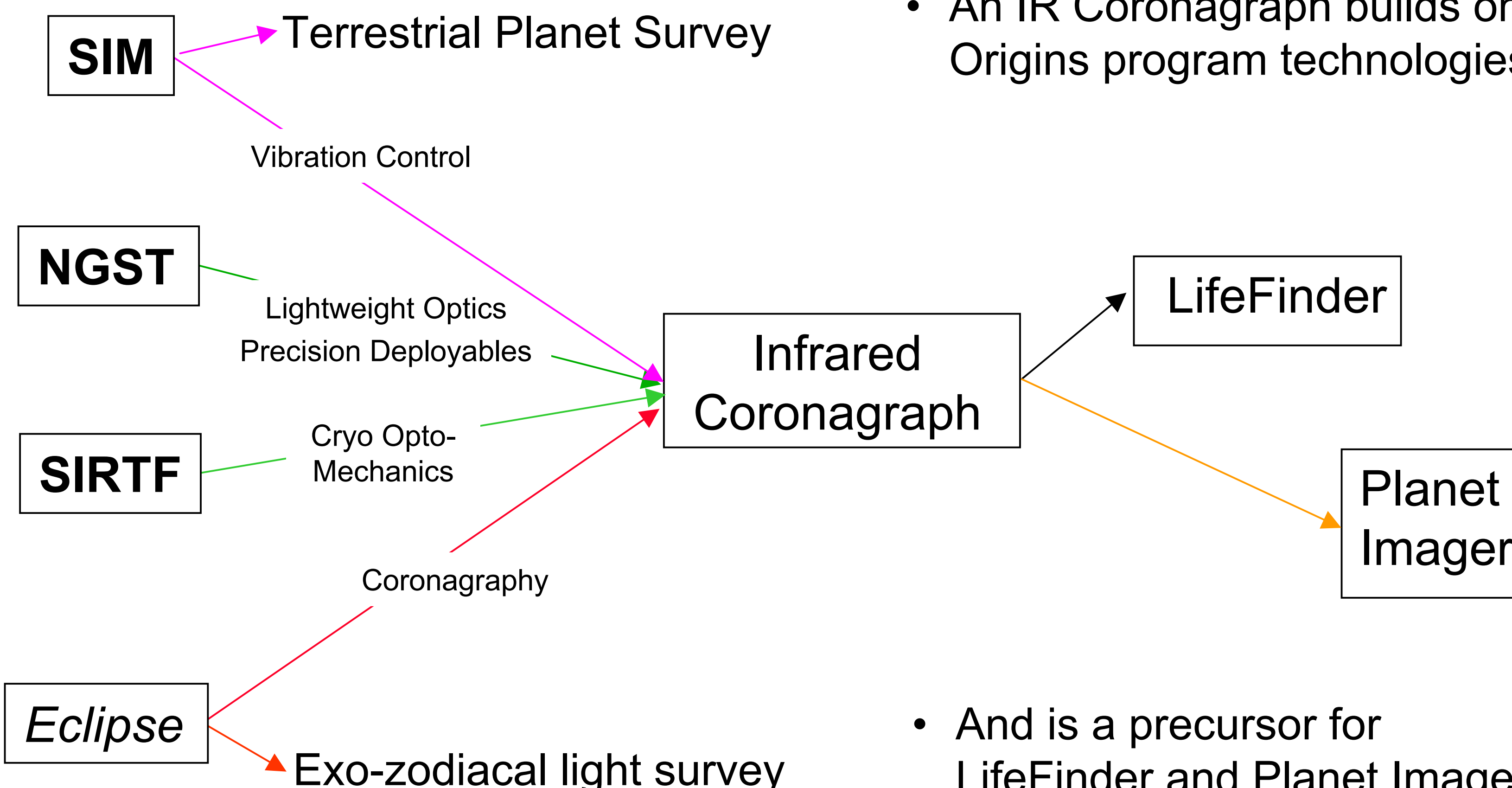


Disks and Jets in active Galactic Nuclei

Program Roadmap

<u>**Current** or *Potential* Programs</u>

- An IR Coronagraph builds on Origins program technologies



- And is a precursor for LifeFinder and Planet Imager

Roadmap to Briefing

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- Introduction
- TPF Requirements
  - Derived requirements and mission concept
- Spacecraft Description
  - Configuration
  - Technical performance
- Science Payload
  - Telescope
  - Instrument
  - Technical and scientific performance
- Break
- Fabrication, Assembly, and Test
- Launch, Commissioning, and Operations
- Technology Development
- Life Cycle Cost Estimate (<$2B)
- Summary

System Engineering

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Even 13 Years Before Launch TPF Requires System Engineering Process

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- Thorough identification and analysis of requirements is needed at this time
- We have defined and flowed down requirements to the level that a configuration can be developed
  - Baseline concept becomes an existence proof for TPF
  - Requirements are used to help identify technology needs
- We have identified and performed preliminary trade studies
- These results provide one possibility of what TPF might look like
  - Further systems analyses will optimize requirements
- A large aperture, IR telescope with coronagraph capability looks like a feasible option for TPF
  - Required technologies are reasonable developments from NGST, SIM, and other programs
  - Architecture provides high performance and adaptability for planet finding and general astrophysics

Design Begins With Top-Level Requirements from PAR

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These requirements are independent of TPF Architecture

Parameter	Requirement	Source
Mission duration	5 year requirement; 10 year goal	RFP
Investigation allocation	50% Planet detection/characterization, 50% Astrophysics	RFP
Number of targets	At least 150 for detection, at least 20 for characterization	RFP
Detection criteria	SNR = 5	TRW
Angular threshold	50 milli-arcseconds	TRW
Sky coverage	4π steradian	TRW
Integration time	<24 hours for detection; <2 weeks for characterization	RFP/TRW
Wavelength range	VIS: 0.5 – 1.5 microns (TBR); IR: 7 - 17 microns	RFP/TRW
Spectral resolution	VIS: at least R = 100 (TBR); IR: at least R = 20	RFP/TRW
Characterization performance	SNR = 5 for spectral lines	TRW/SWG
Number of revisits	2 for detection, 7 total (including characterization)	SWG
Revisit frequency	No less than 1 month	SWG

RFP refers to Exhibit II in TPF RFP; TRW refers to requirements derived by the TRW Science Team; SWG refers to requirements derived at the September meeting of the TPF Science Working Group.

Requirements Flowdown Process Refines Requirements from PAR

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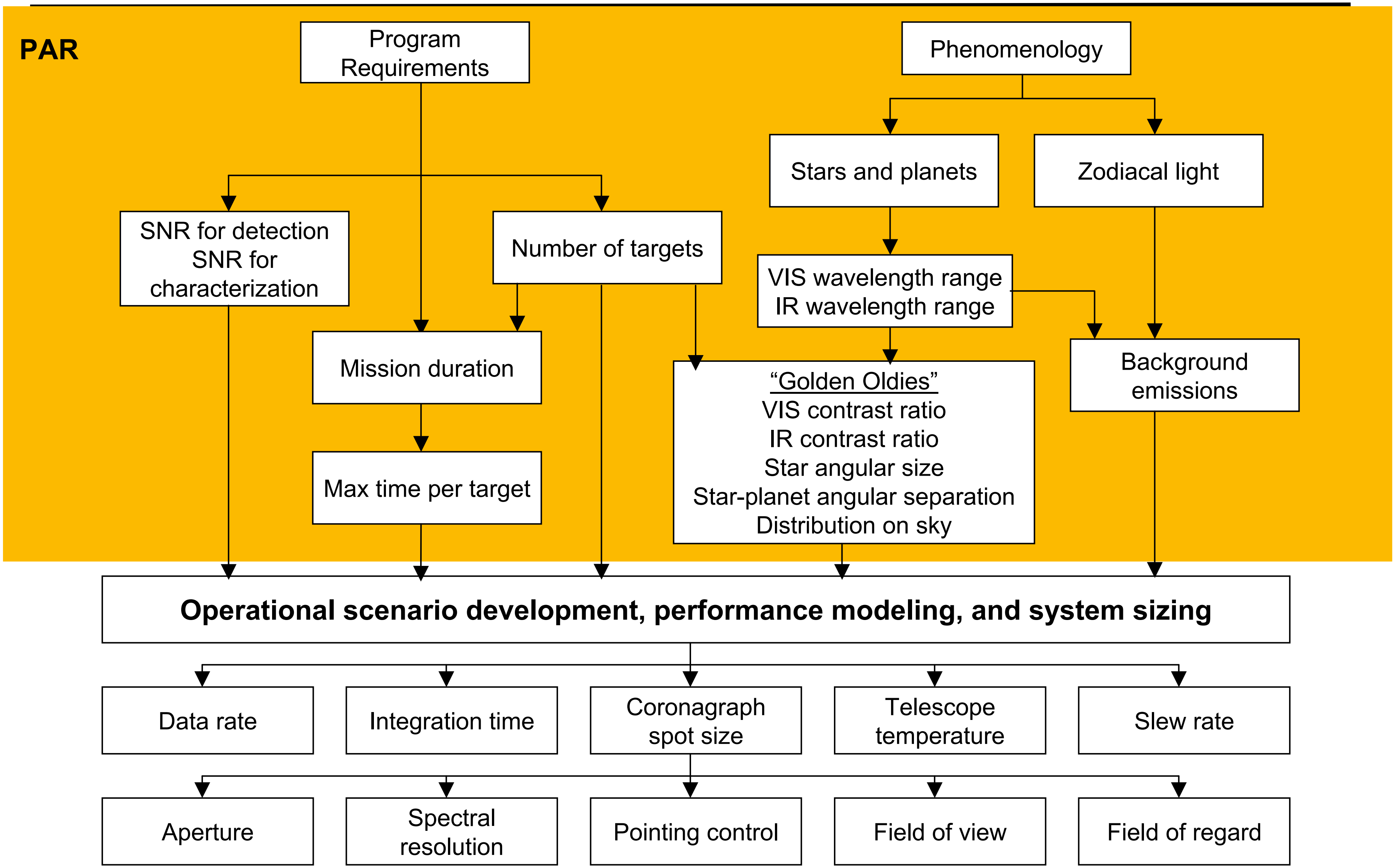

A Single Requirement Can Impact Many Areas

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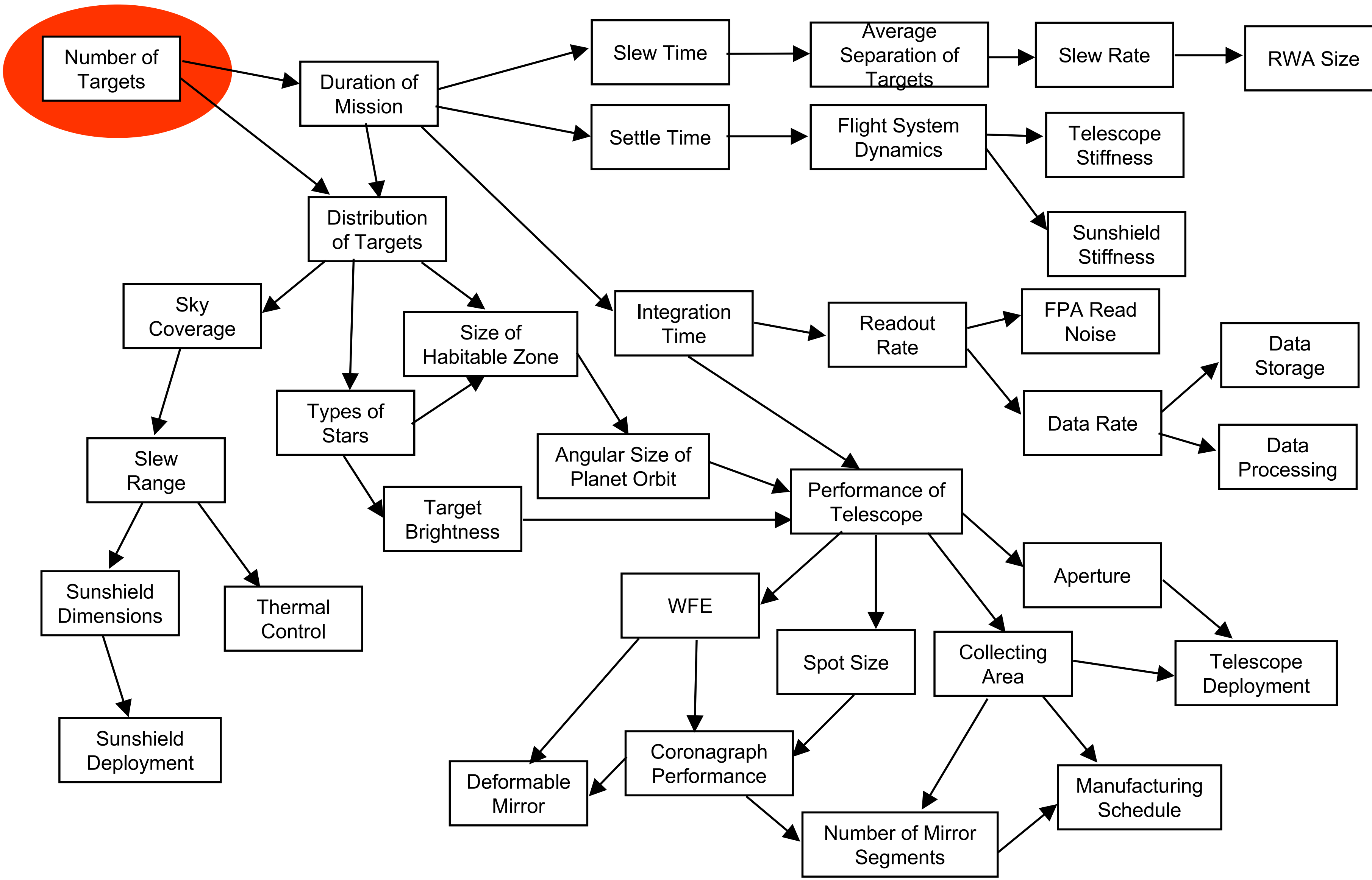

Key Requirements Derived from Flowdown and Allocation Process

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Requirement	Derivation and Comments
28-m aperture	Derived from performance modeling
36-hex configuration, 4-m flat-to-flat hexes	Derived from stowing requirements and coronagraph performance
5 kg/m^2 primary mirror areal density	Allocation based on extrapolation of NGST technology development
5 μm requirement; 2 μm goal diffraction limit	Derived from coronagraph performance requirements and extrapolations from NGST
5 arcsec observatory pointing accuracy	Allocation based on NGST performance
6-hour average detection integration time	Operations allocation based on the Earth at 10 pc
180-hour average characterization integration time	Operations allocation based on the Earth at 10 pc
10 deg in 1 hour slew rate	Based on average target separation and operations allocation
30 deg x 360 deg field of regard	Allows minimum of 2 months/year accessibility to all ecliptic latitudes
<50K telescope operating temperature	Based on requirement to be background-limited
100 mas occulting spot diameter	Derived from planet-star separations in “Golden Oldies” list
1000 s FPA readout rate	Based on NGST to minimize cosmic ray interference

Key Requirements (Continued)

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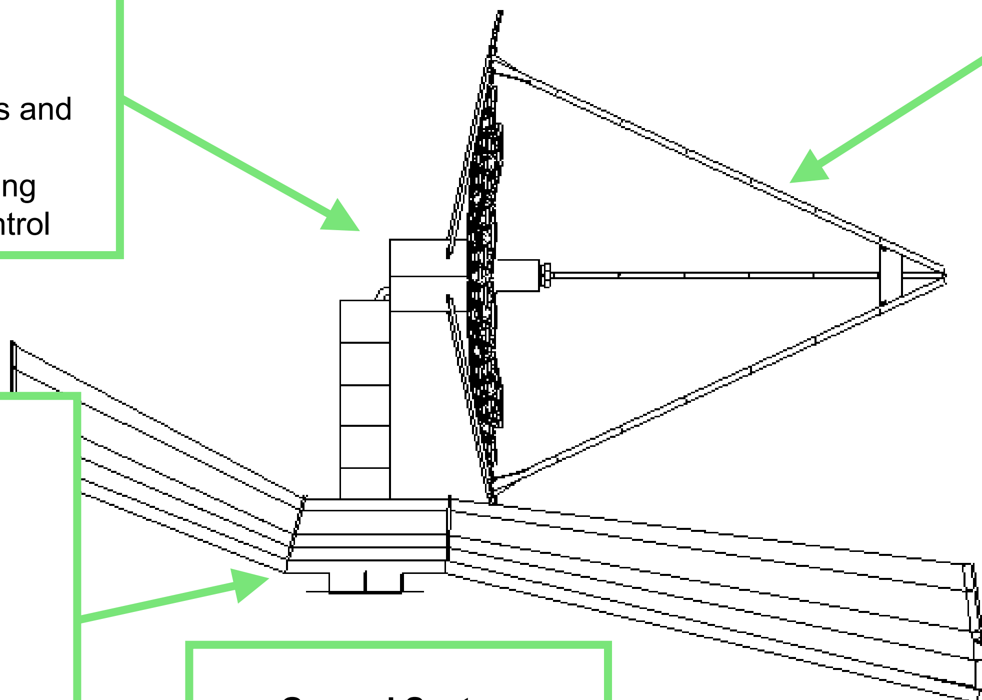
Requirement	Derivation and Comments
10 arcsec FOV for coronagraph	Derived from coronagraph modeling
1 arcmin FOV for general astrophysics	Allocation agreed to by science team and derived from telescope optics modeling
3 milliarcsec (3 σ) fine pointing	Allocation based on coronagraph modeling
30 nm Primary Mirror WFE	Allocation based on coronagraph modeling
88 – 349 kbps raw science data rate	Derived from strawman instrument complement
15 – 60 Gbits raw science data storage	Assuming 2 days storage of raw science data
0.5 – 2.1 Mbps raw science data downlink	Transmit all raw science in one 8-hour pass
December 2014 launch date	Assigned by program

We Have Defined Mission Elements

Science Instrument Module
- FPAs and Cold Electronics
- Instrument Optics and Coronagraph
- Instrument Housing and Thermal Control

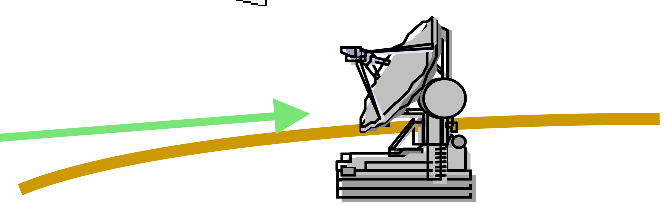
Flight System

Optical Telescope Assembly
- Primary Mirror
- Secondary Mirror and Support Structure
- Downstream Optics and Deformable Mirror



Spacecraft Bus
- Command and Data Handling
- Power
- Propulsion
- Attitude Control
- Warm Payload Electronics
- Telecommunication
- Sunshades
- OTA Support Structure

Ground System
- Receive data and telemetry downlink
- Uplink commands and software modifications
- Wave control software
- Level 1 data processing
- Operations planning



Functional Requirements Have Been Allocated to Each Element

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Ground System	Commands Software Uploads		
Science Data P/L Telemetry SOH Data Wave Front Data	**Spacecraft**	Commands Power Thermal Control Attitude Control	Commands Power Thermal Control Attitude Control
	Science Data SOH Data Pointing Data Wave Front Data	**Science Instrument Module**	Thermal I/F Mechanical I/F
	Configuration Data SOH Data	Starlight	**Optical Telescope Assembly**

Flight System

We Have Baselined L2 for the Large IR Telescope with Coronagraph

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- Operating cryogenic telescope easier at L2 than Earth orbit
  - No Earth thermal input to consider
  - Can maintain Sun on one hemisphere of spacecraft
- Attaining large sky accessibility easier from L2 than Earth orbit
  - No Earth avoidance required
- Communications easier to accommodate at L2 than in heliocentric drift away orbit
  - Nearly constant range
  - High gain pointing easier to implement
  - Simple downlink scheduling

Mission is Divided into Separate Phases

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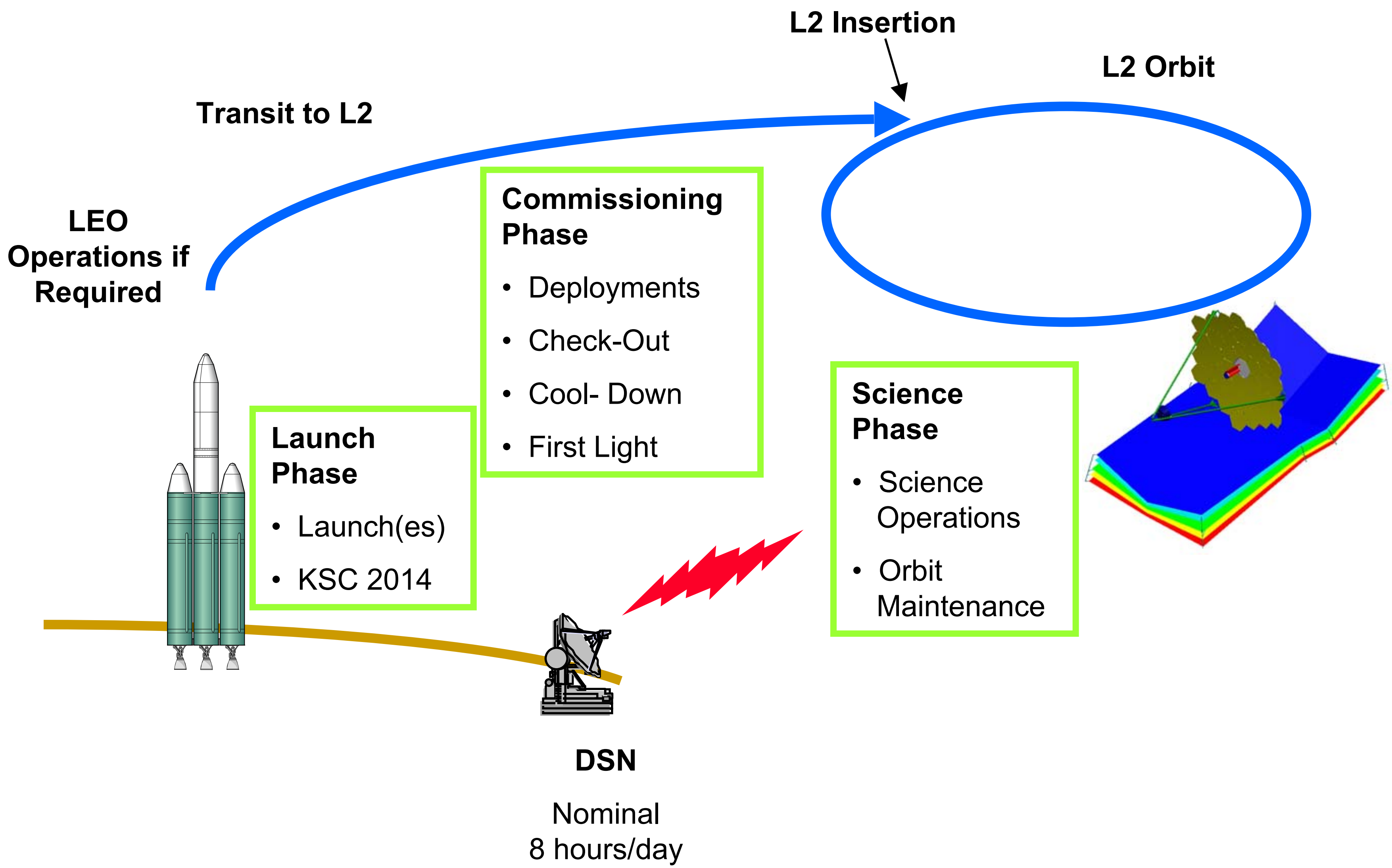

We Have Adapted Primary Mirror Concepts From NGST and Keck

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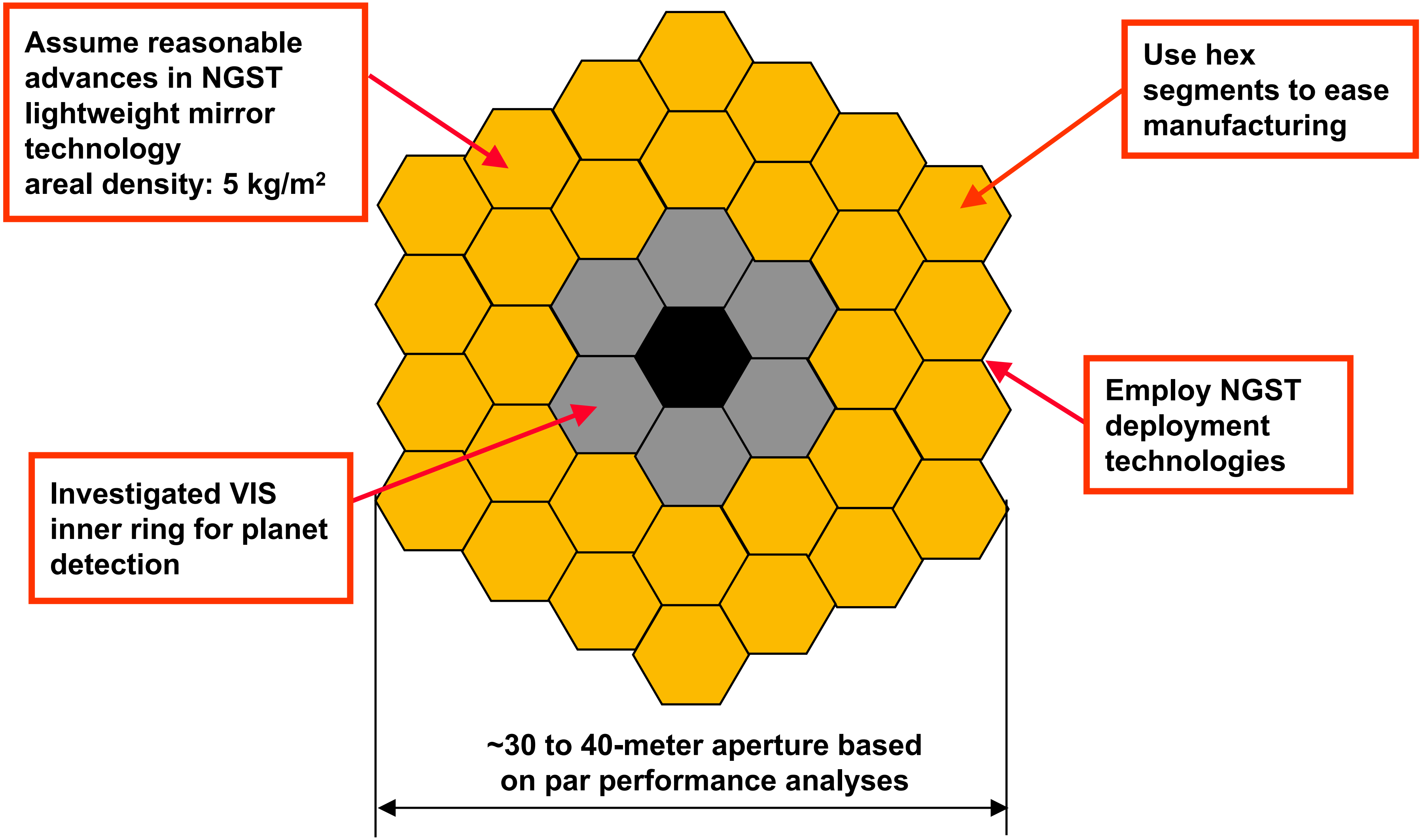

VIS Inner Ring Did Not Turn Out To Be a Beneficial Option

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- VIS inner ring was originally proposed as a way to enhance detection performance and increase science
- VIS inner ring would have been initial stage in incremental buildup of large aperture
  - VIS aperture of 12 to 18 meters
- Practical considerations diminished the desirability of this option
  - Low exo-planet flux in VIS provides no performance advantage over IR
  - VIS inner ring adds considerable mass to the Observatory
    - Assuming 25 kg/m^2 for VIS the additional mass would be 1600 to 3800 kg
  - VIS capability complicates coronagraph and adds new focal plane
  - Combining VIS and IR requires cryogenic and non-cryogenic instrumentation in close proximity
  - All lightweight IR telescope reduces number of launches preventing the need for incremental telescope build-up in orbit

Allocations and Performance Modeling Provide Size of Minimum Aperture

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5-year mission x 365 days x 24 hours/day

÷ 2 for planet finding

÷ 2 for planet detection

Program Allocations

= 10,950 hours for detecting planets

÷ 150 targets

÷ 3 visits per target

Science Requirements

= 24.3 hours per target

- 1 hour for slewing and settling

Operational Allocations

= 23.3 hours max for integration per target

"Golden Oldies" Target List

Performance Model

28-meter aperture adequate for dimmest targets

Selected Baseline Primary Mirror to Balance Performance and Cost

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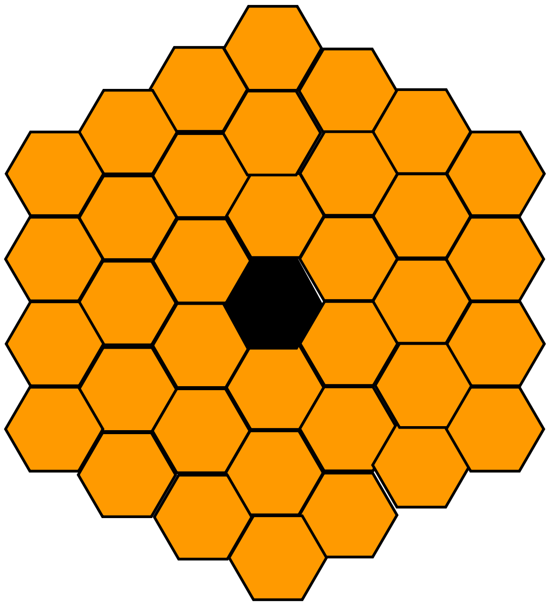
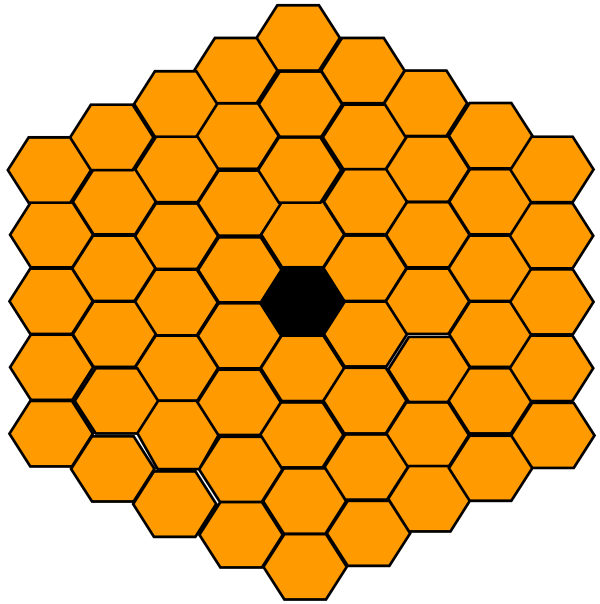


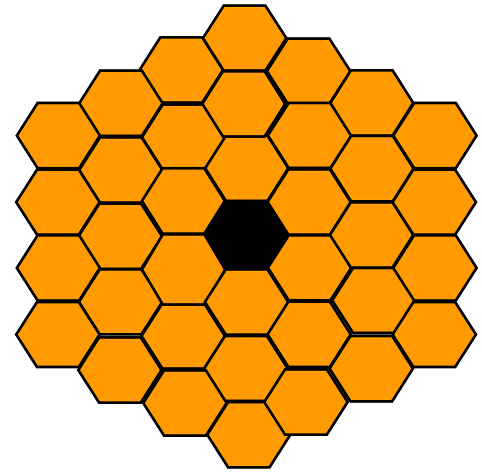
New 7-meter Class
Fairing Allows 40-meter
PM with 36 Hexes

Best Performance
Major LV Development



Lengthened 5-meter Class
Fairing Allows 36-meter
PM with 60 Hexes

Good Performance
Moderate LV
Development



Standard 5-meter Class
Fairing Allows 28-meter
PM with 36 Hexes

Adequate
Performance
No LV Development
Upgraded by Adding
Fourth Ring

Fine Pointing and Mirror Stability Allocations Within Feasible Limits

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Star-Planet Contrast Ratio

Apodized Occulting Spot and Lyot Mask Performance

Uncompensated PSF Errors

- Control Star on Occulting Spot
- Control PM Vibration

Allocations

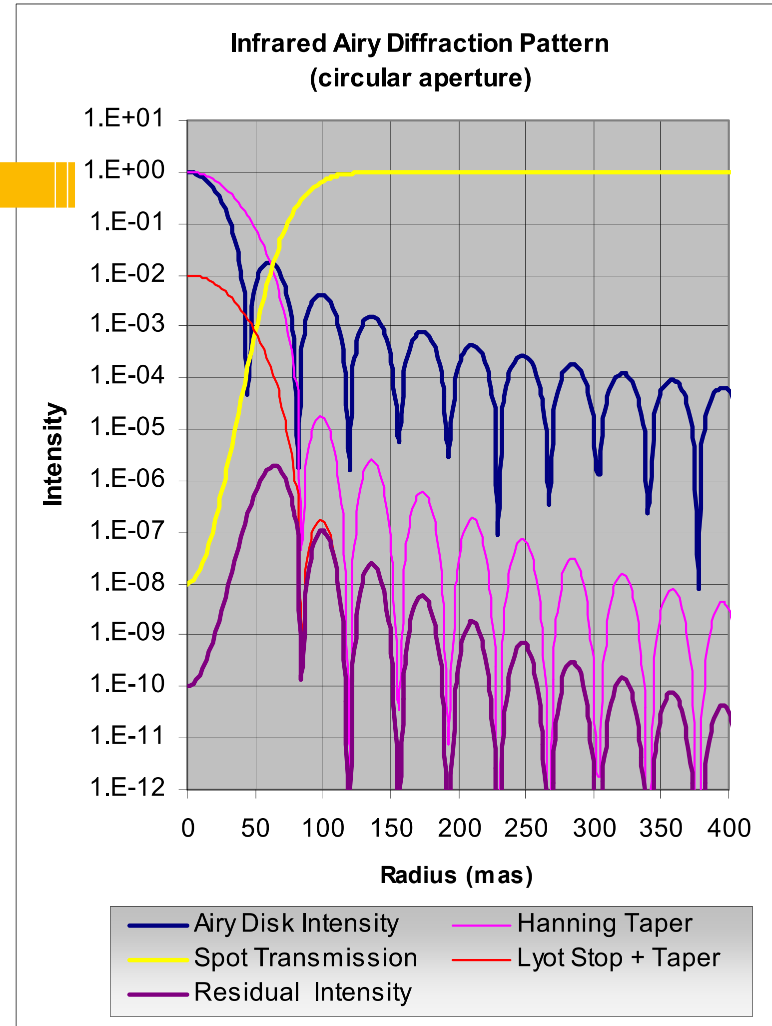
- 3 mas
- 3 mas

30 nm rms PM WFE for 4.5-m segments

Adapt NGST and Eclipse fine pointing strategies

Adapt SIM vibration damping technologies

Model Results



Performance Model Confirms Allocations and Shows Margin

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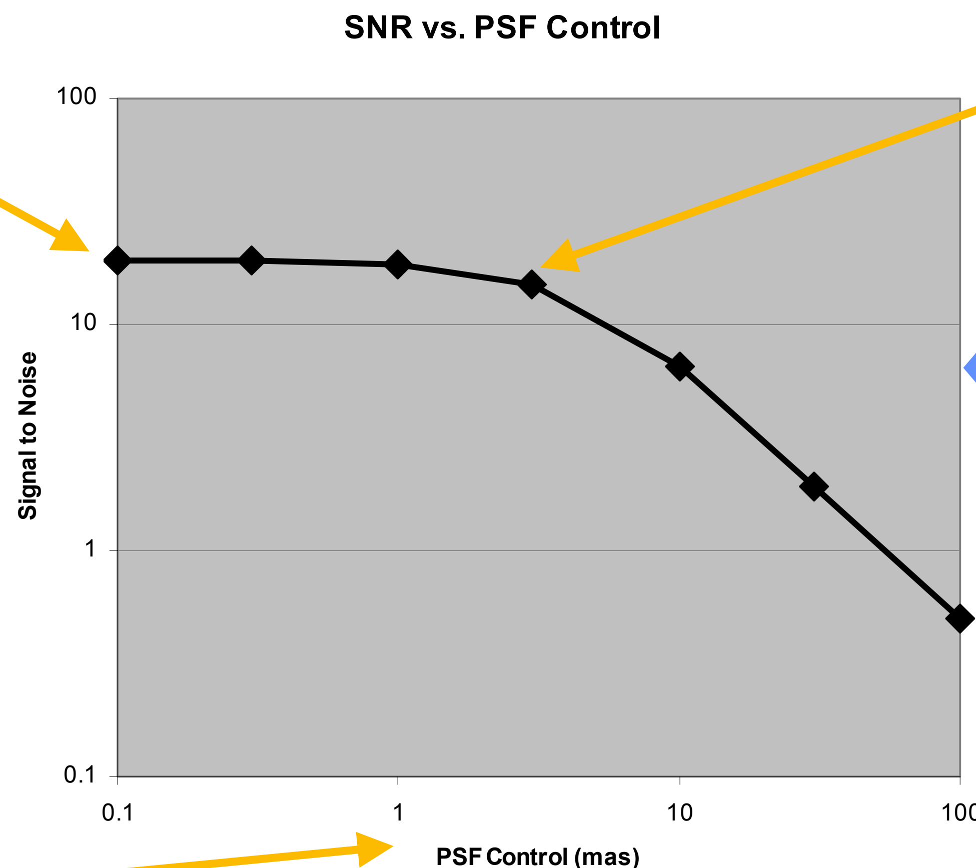
SNR computed for Earth at 10 pc with 2-hour integration

3 mas allocation near “knee” in SNR curve



SNR = 5 Requirement

PSF control allocated equally between PM vibration and fine pointing

4π Sky Coverage Requirement Determines Basic Configuration

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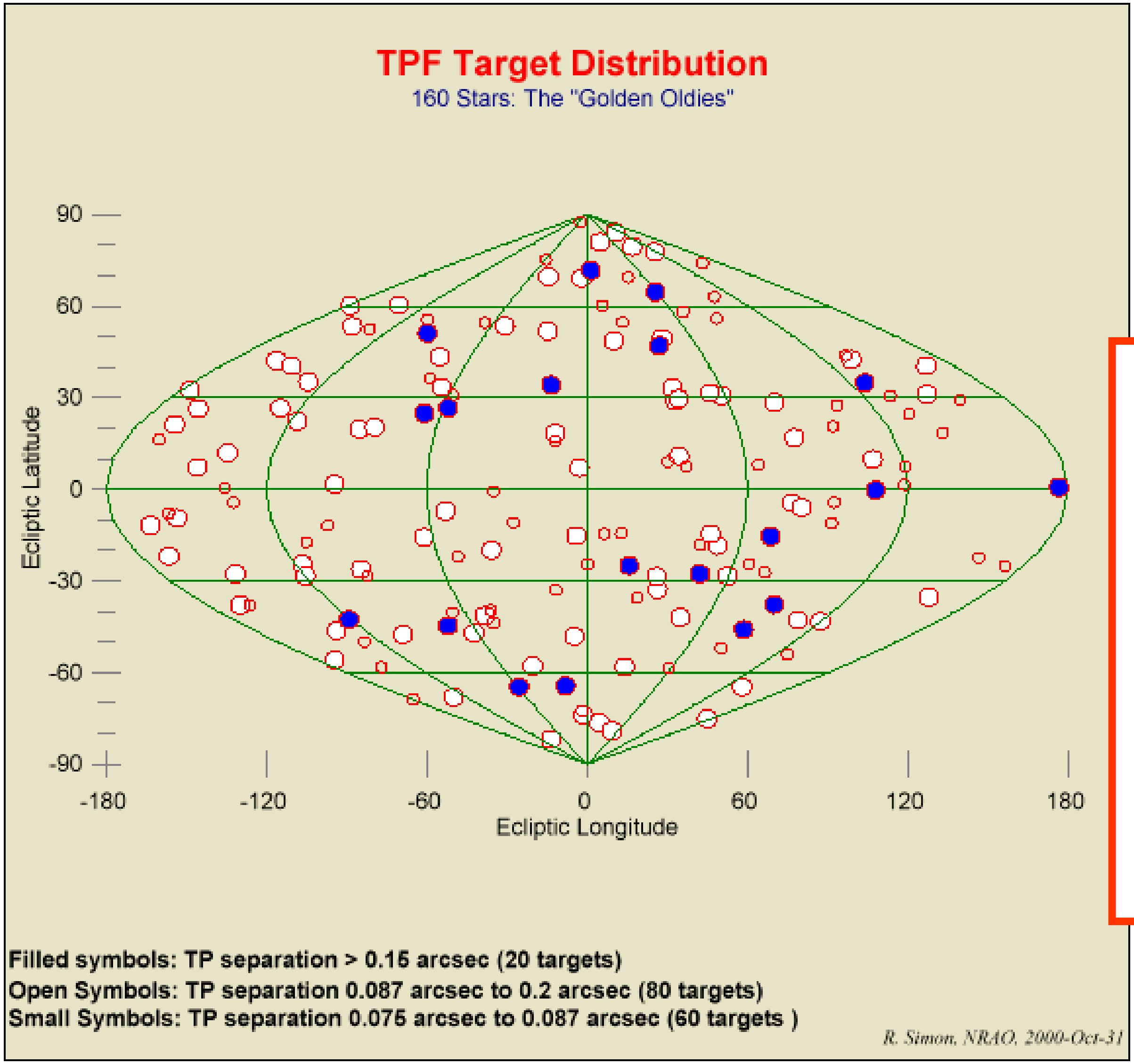

- **Potential targets are evenly distributed on the sky**
- **Less than full sky accessibility would require Observatory to find targets at greater distances, requiring higher performance (for example, larger aperture)**

Side-Looking Configuration Accomplishes Sky Coverage Best

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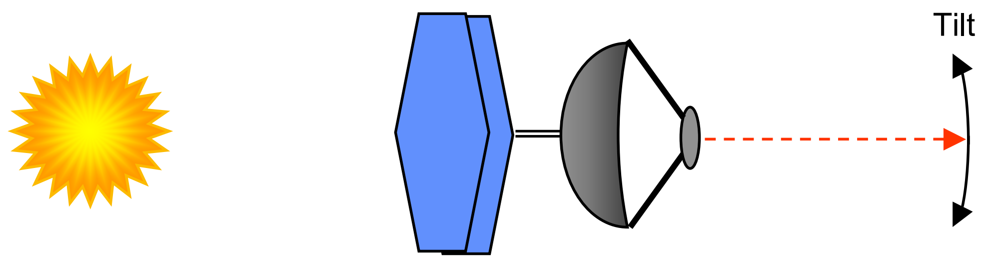
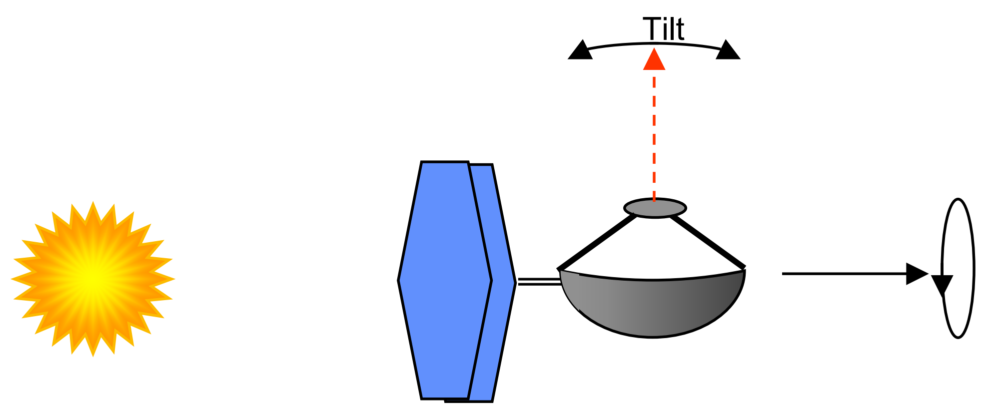
Up-Looking Configuration



Nominal Boresight Points Anti-Sunward

Observatory must "tilt" 90 degrees to observe ecliptic pole, which causes sunshield to get infinitely large

Side-Looking Configuration



Nominal Boresight Points Orthogonal to Sun-Line

Observatory can rotate about sun-line to cover all ecliptic latitudes. Tilt determines size of field of regard

Adequate Field of Regard Required to Observe All Targets

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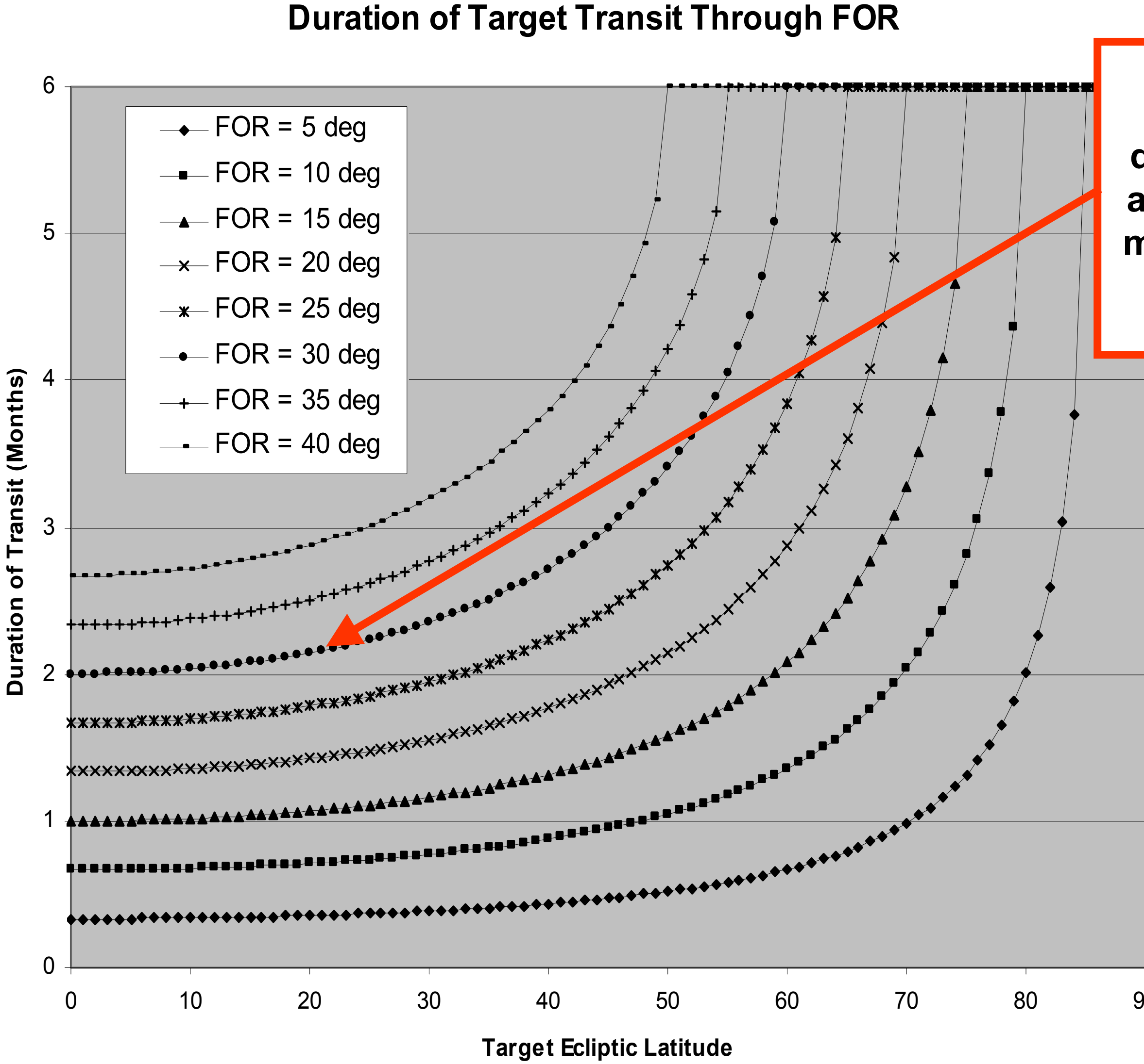

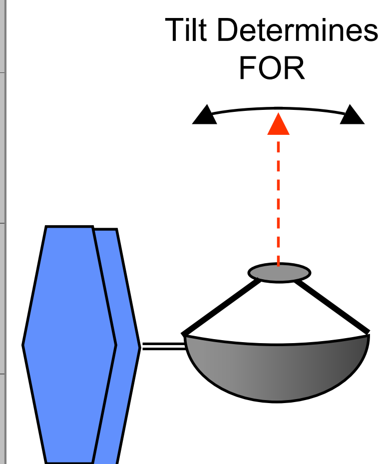

Large IR Aperture with Coronagraph Is an Attractive TPF Option

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- Our results show that a large IR observatory that detects and characterizes exo-solar planets using a coronagraph should be realizable within the TPF program timeframe
- NGST and SIM technologies provide solid basis for TPF development
  - NGST mirror and deployment technologies
  - SIM vibration control technology
  - Eclipse coronagraph testbed technology

Our TPF Architecture Meets All Evaluation Criteria

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Architecture Suitability Questions	IR Coronagraph Response
1) How well does the proposed architecture meet the primary goals of TPF? a) Can it detect Earth-like planets around a statistically interesting number of stars during the nominal mission duration, in less than half of 5-year mission b) Does it cover wavelengths that are indicative of 10 the presence of an atmosphere, 2) habitability, 3) extant life?	Our architecture completes the detection and characterization mission in 2.5 years. The 7-17 μm wavelength range covers absorption lines for water, methane, ozone, carbon dioxide.
2) Do the signal to noise calculations include reasonable assumptions about the targets (stars and planets), important instrumental efficiency terms, and important noise sources with reasonable values (including astrophysical sources)?	Our performance model includes local and exo-zodiacal emissions, jitter, thermal emissions, reflectance, read noise, quantum efficiency. We have furthered modeled the effects of apodization and wavefront performance requirements.
3) Can the architecture provide information on full range of objects and structures in the planetary systems being studied (e.g., giant planets, exo-zodical dust clouds, etc.).	The large aperture provides excellent performance for both point sources and extended structures.
4) Does the proposed architecture have a natural scientific precursor of more limited scope? List scientific goals, legacy to TFP, mission size (by cost or analogy).	The Eclipse mission provides a precursor to validate coronagraph technology and explore evolving or mature planetary systems. Eclipse is a Discovery-class mission.
5) What is the potential of this architecture for general astrophysical observing?	Our architecture provides a logical follow-on to NGST, with greater imaging and spectroscopic resolving power.

Terrestrial Planet Finder

Evaluation Criteria (Continued)

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Architecture Suitability Questions	IR Coronagraph Response
6) How would the requirement for a general astrophysical capability affect the facility (e.g., complexity, additional instruments, target limitations, mission lifetime)?	The planet finding/characterization instrument can already accomplish a wide range of general astrophysics goals. Our architecture can easily accept additional specialized instrumentation. It can investigate a wide range of target types and general astrophysics is already factored into the mission lifetime.

Observatory Configuration

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Agenda

- Agenda
- Introduction
- Study Process
- Observatory Configuration
- Spacecraft Straw man Configuration
- ISIM Structure
- Weight/Power
- Deployable Technologies
- Attitude Control Subsystem (ACS)
- Data Management Subsystem (DMS)
- Dynamics
- Thermal
- Launch
- Summary

A Large IR Observatory Is Feasible in TPF Timeframe

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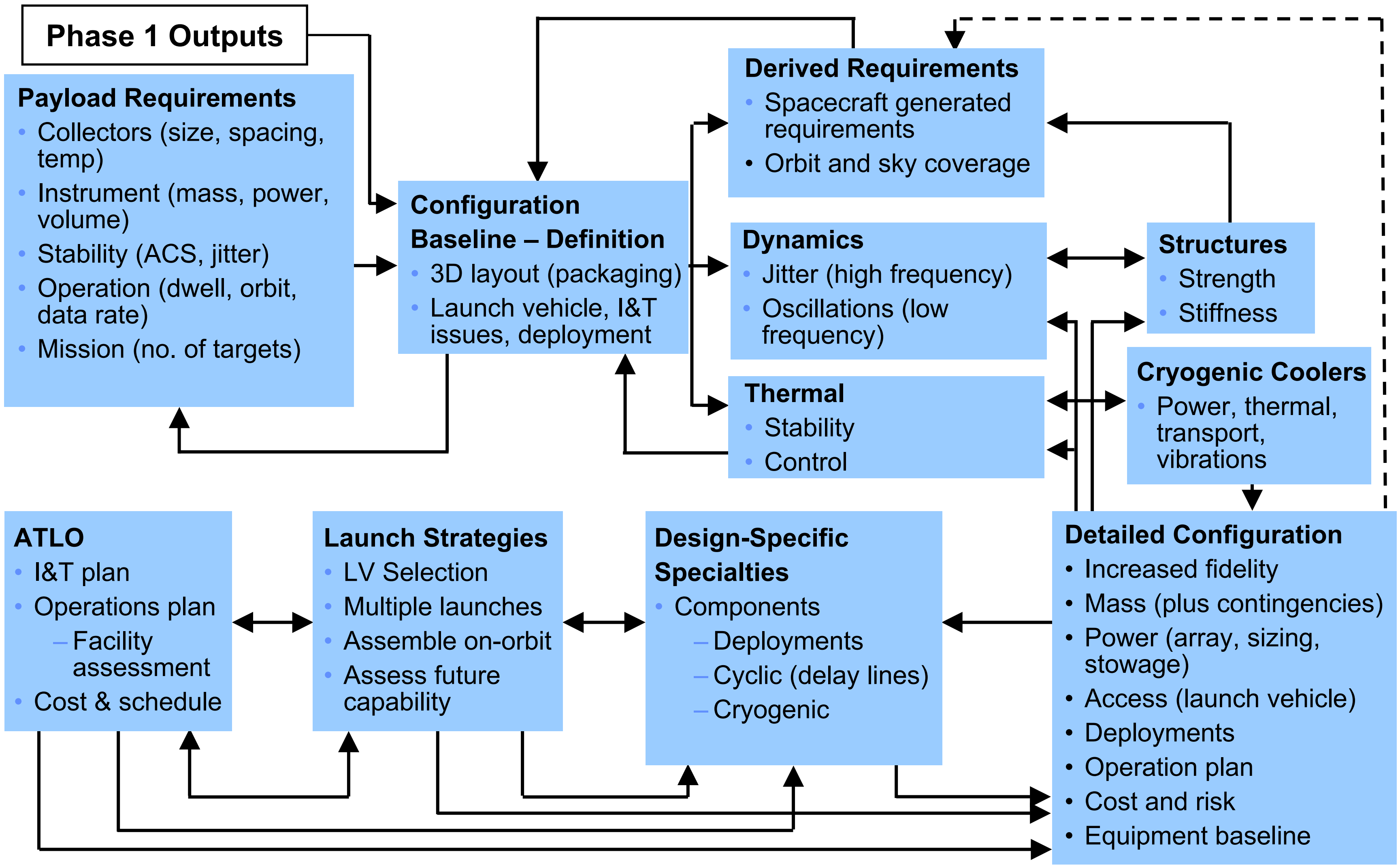
- Spacecraft technologies needed to meet the requirements of the coronagraph architecture are direct evolutions of SIM, NGST, and other missions
  - Structural stability and jitter control are derived from SIM
  - Sunshades/thermal control is scaled up from NGST
  - Pointing requirements are well within current capabilities (i.e., Chandra)
  - C&DH, Comm, Power, Propulsion from existing programs
  - Deployments use technologies developed on SIM, NGST, and other missions
- Observatory can be launched to and operated from L2
  - Stows into currently planned 5-meter fairings
  - Mass, including margin, within the performance capabilities of planned launch vehicles
    - Two-Launch option mitigates risks from mass growth

Configuration Team Study Process



Straw man Configuration Deployed – Anti-Sun Side

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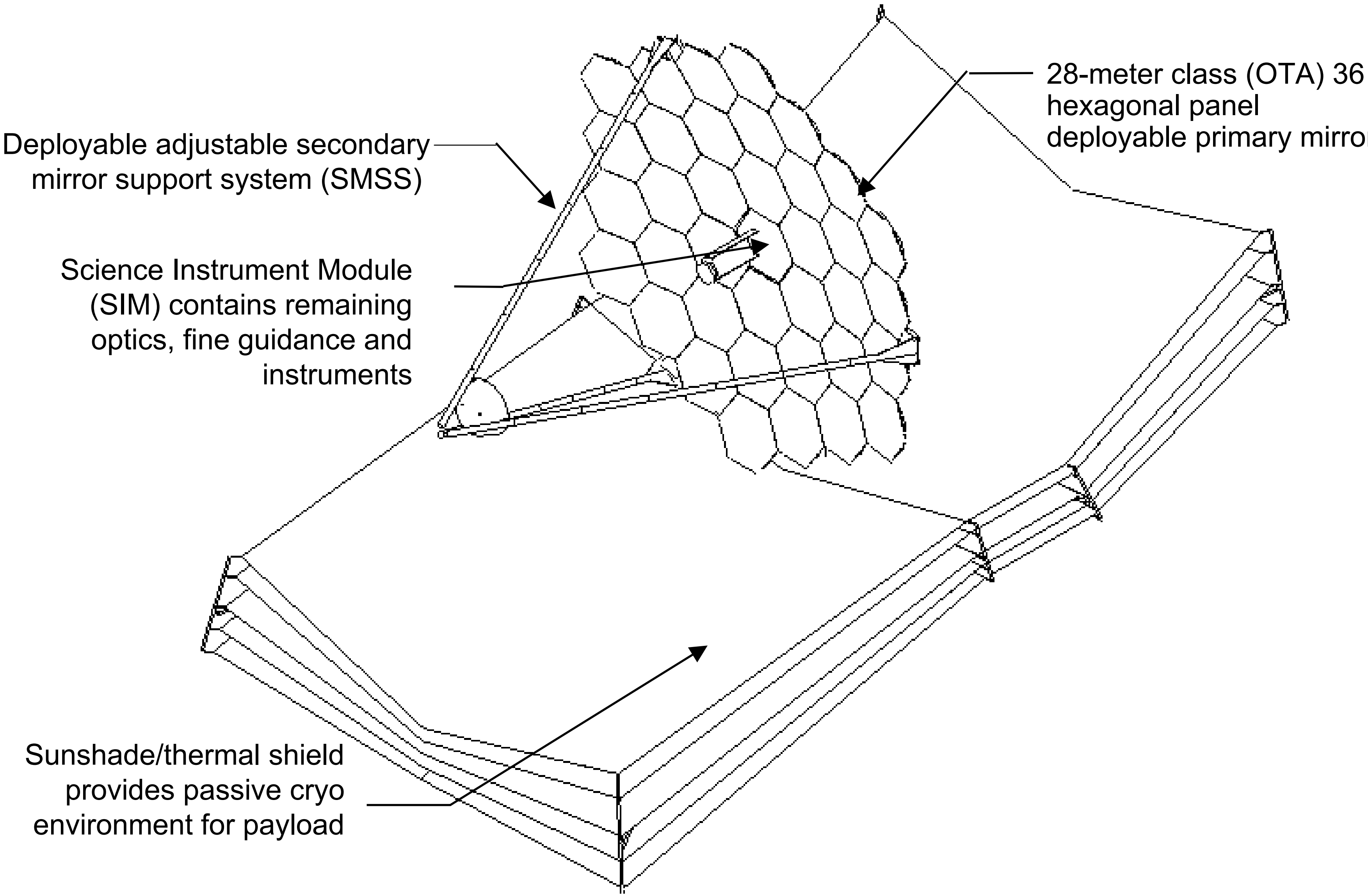

Straw man Configuration Deployed – Sun Side

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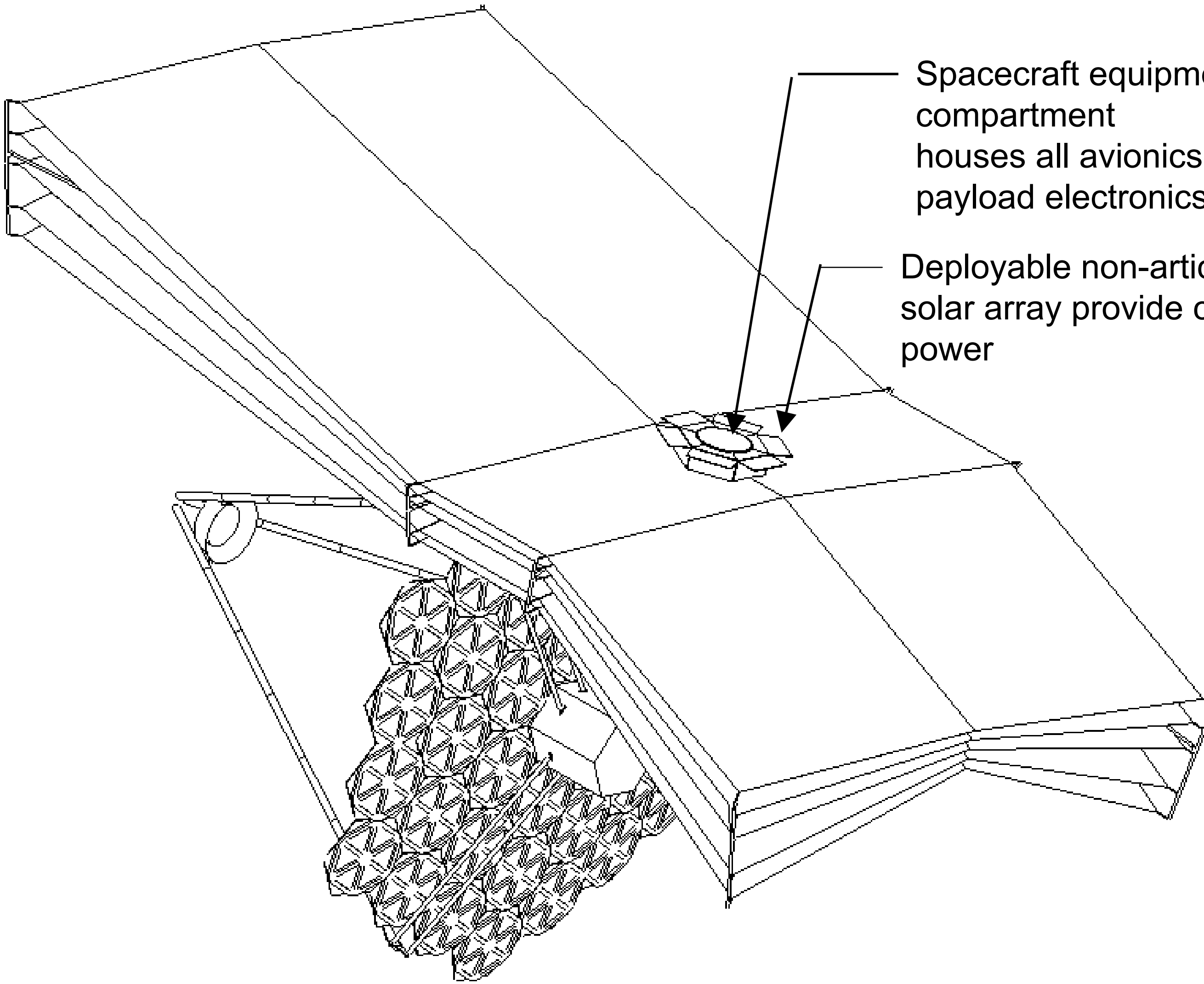

Spacecraft equipment compartment
houses all avionics and payload electronics

Deployable non-articulating solar array provide constant power

Deployed Dimensions

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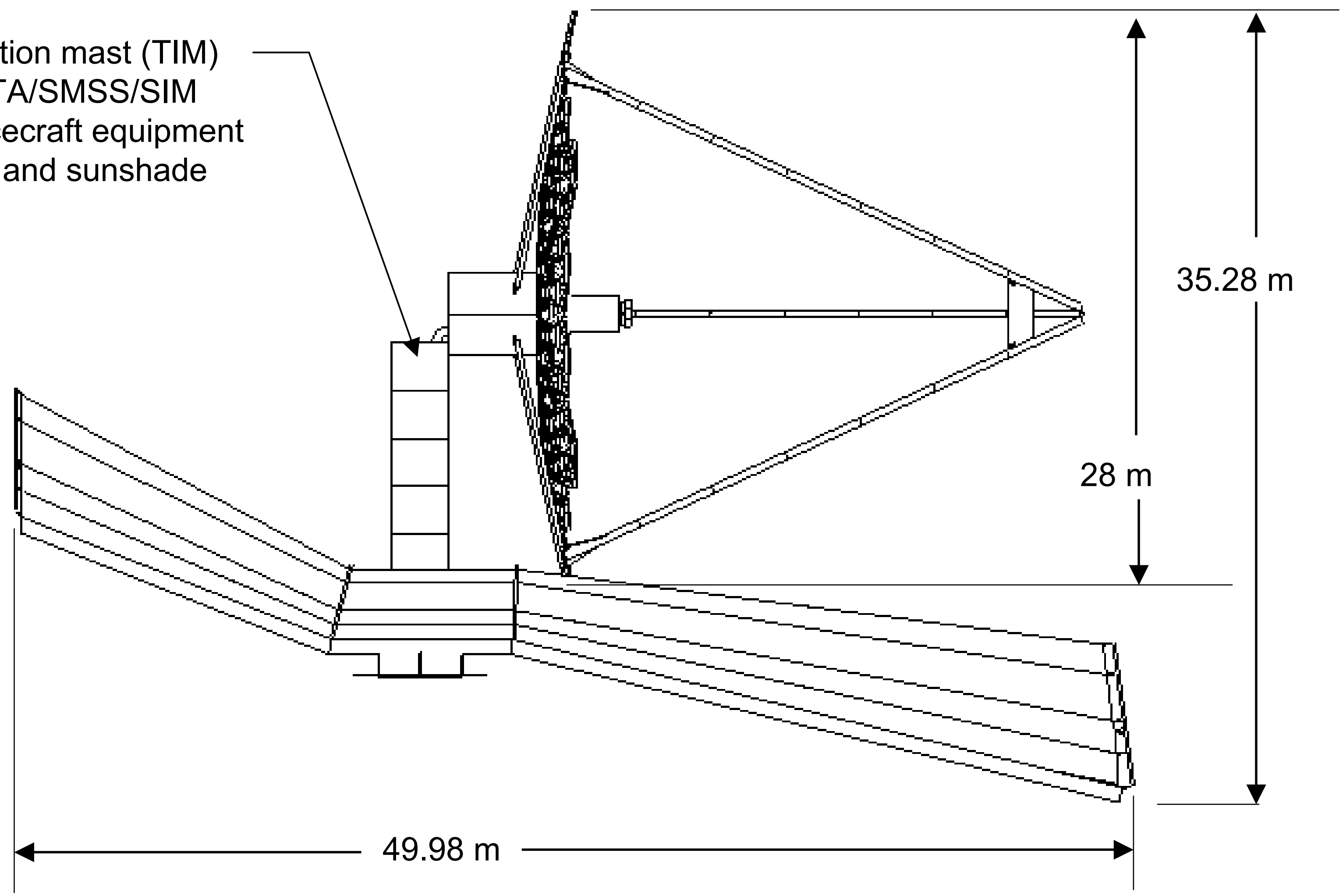
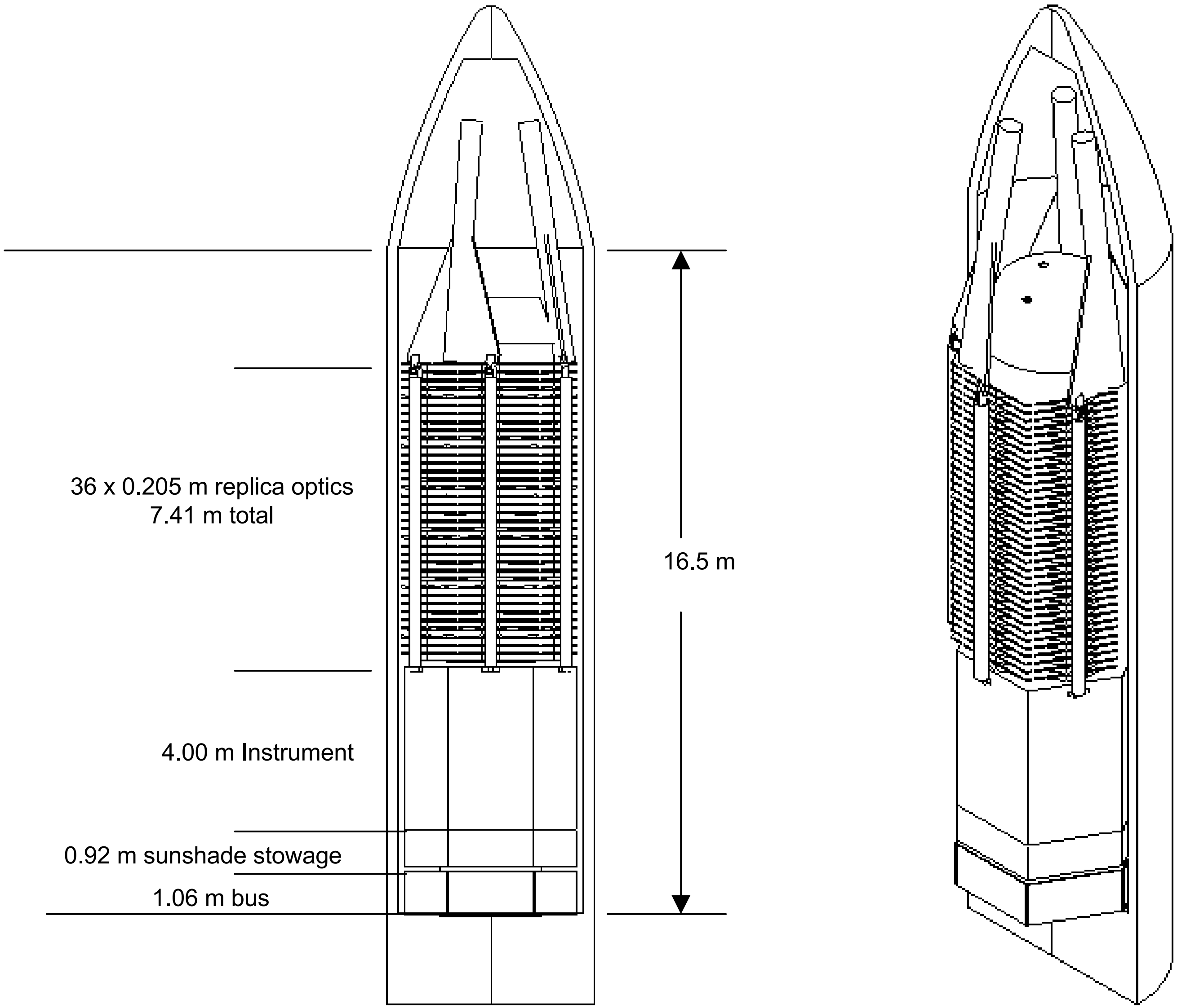
Thermal isolation mast (TIM) Separates OTA/SMSS/SIM from the spacecraft equipment compartment and sunshade



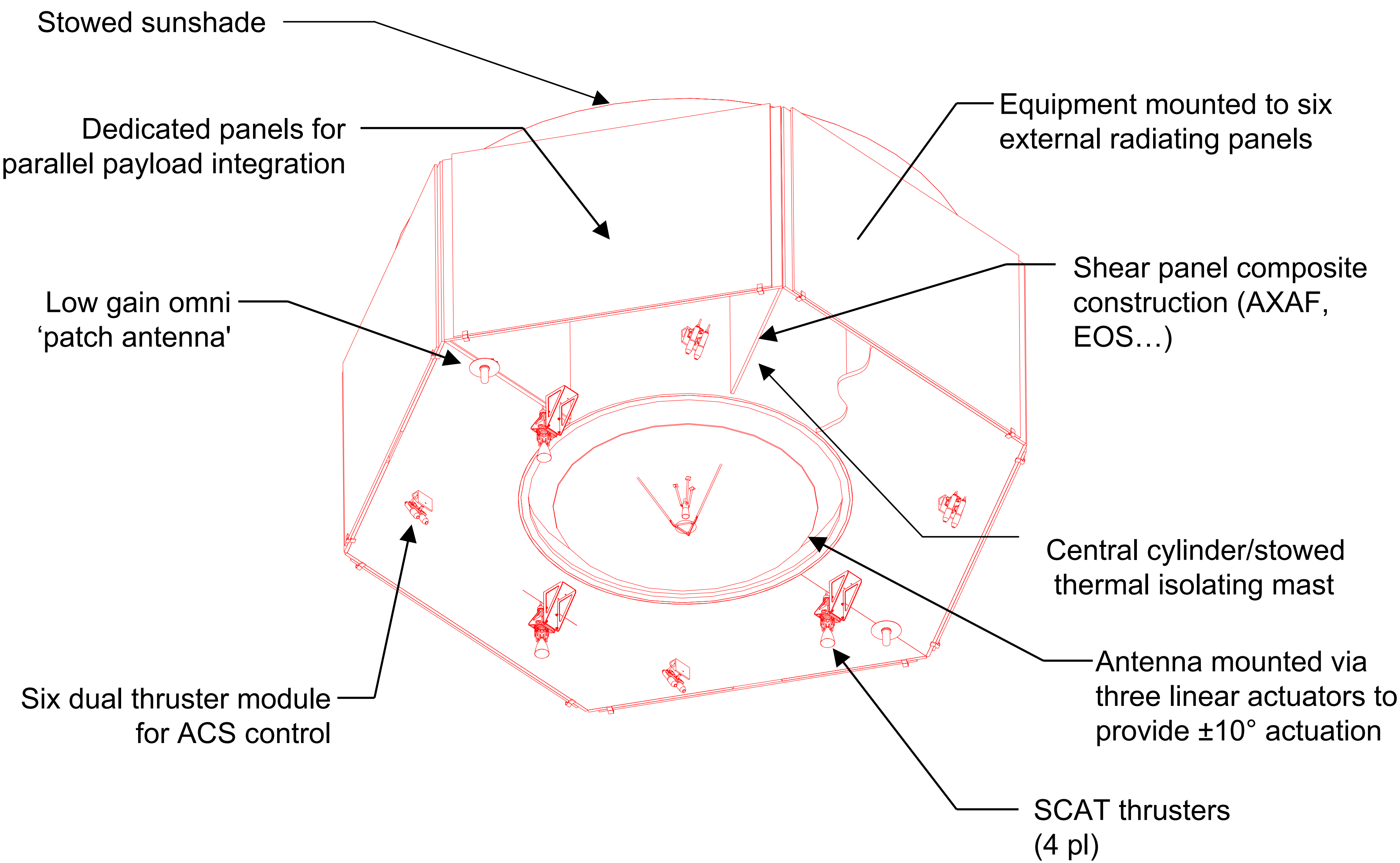
Stowed Dimensions in 73.5 Foot Fairing

TRW



Strawman Spacecraft Summary

TRW



Weight Summary

TRW

	Estimated Unit Weights (kg)	Launch Weight (kg)	Launch Weight (lb)
OPTICAL TELESCOPE ASSY ALLOCATION	4,245.4	4,245.4	9,053.0
PRIMARY MIRROR	3,580.8	3,580.8	7,877.8
SECONDARY MIRROR ASSEMBLY	150.2	150.2	330.5
TERTIARY/DM MIRROR ASSEMLY	130.4		
DEPLOYABLE MIRROR MAST	312.0	312.0	686.4
OTA ELECTRONICS (in Bus)	72.0	72.0	158.4
INSTRUMENT MODULE ALLOCATION	1,044.2	1,044.2	2,297.2
INSTRUMENT MODULE STRUCTURE	204.2	204.2	449.2
SCIENCE INSTRUMENTS	800.0	800.0	1,760.0
INSTRUMENT ELECTRONICS (in Bus)	40.0	40.0	88.0
SPACECRAFT BUS	1,840.0	1,840.0	4,048.0
STRUCTURE & MECHANISMS	668.8	668.8	1,471.4
THERMAL CONTROL	622.9	622.9	1,370.4
PROPULSION	116.2	116.2	255.7
ELECTRICAL POWER	174.7	174.7	384.3
GUIDANCE, NAVIGATION & CONTROL	173.1	173.1	380.9
DATA MANGEMENT	37.3	37.3	82.1
COMMUNICATIONS & DATA TRANSMISSION	46.9	46.9	103.2
DRY LAUNCH WEIGHT	7,129.6	7,129.6	15,685.1
PROPELLANTS	654.8	654.8	1,440.6
LAUNCH VEHICLE ADAPTER (3% OF TOTAL)		233.5	513.8
TOTAL LIFT-OFF WEIGHT		8,017.9	17,639.5
LAUNCH VEHICLE THROW WEIGHT TO L-2		11,000.0	24,200.0
LAUNCH MARGIN		37.2%	37.2%

Power Summary

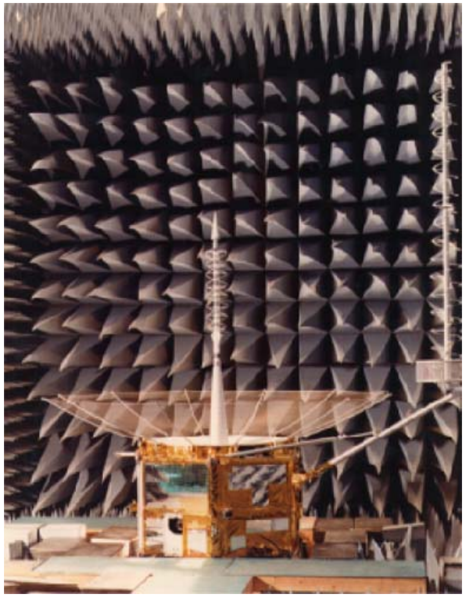
TRW

	Estimated Unit Power (W)	On-station Max. Power EOL (W)
INSTRUMENT SUPPORT ELECTRONICS	82.0	112.0
OTA ELECTRONICS	52.0	52.0
INSTRUMENT ELECTRONICS	30.0	60.0
SPACECRAFT BUS	931.8	934.0
THERMAL CONTROL	100.0	100.0
PROPULSION	110.0	110.0
ELECTRICAL POWER	43.7	43.7
GUIDANCE, NAVIGATION & CONTROL	343.8	339.0
DATA MANGEMENT	112.7	112.7
COMMUNICATIONS & DATA TRANSMISSION	221.6	228.7
SYSTEM LOAD POWER		1,046.0
SYSTEM OVERHEAD (7.5%)		78.5
TOTAL SYSTEM LOAD		1,124.5
EOL SOLAR ARRAYS OUTPUT		1,800.0
EOL SYSTEM POWER MARGIN		60.1%

TRW Has Unmatched Depth and Breadth in Space Deployments

TRW

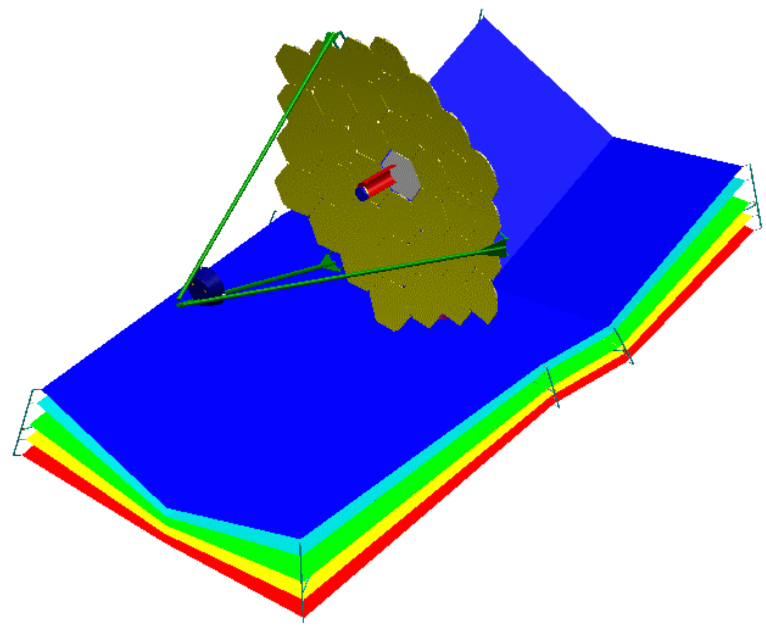
- Never had a mission failure due to deployment anomaly
- Over 40 years of experience in the design, manufacture, integration, verification, and flight operation of spacecraft deployments
- 100% mission success rate
  - 672 deployable systems
  - 1920 individual elements



TRW Expertise Meets TPF Challenges

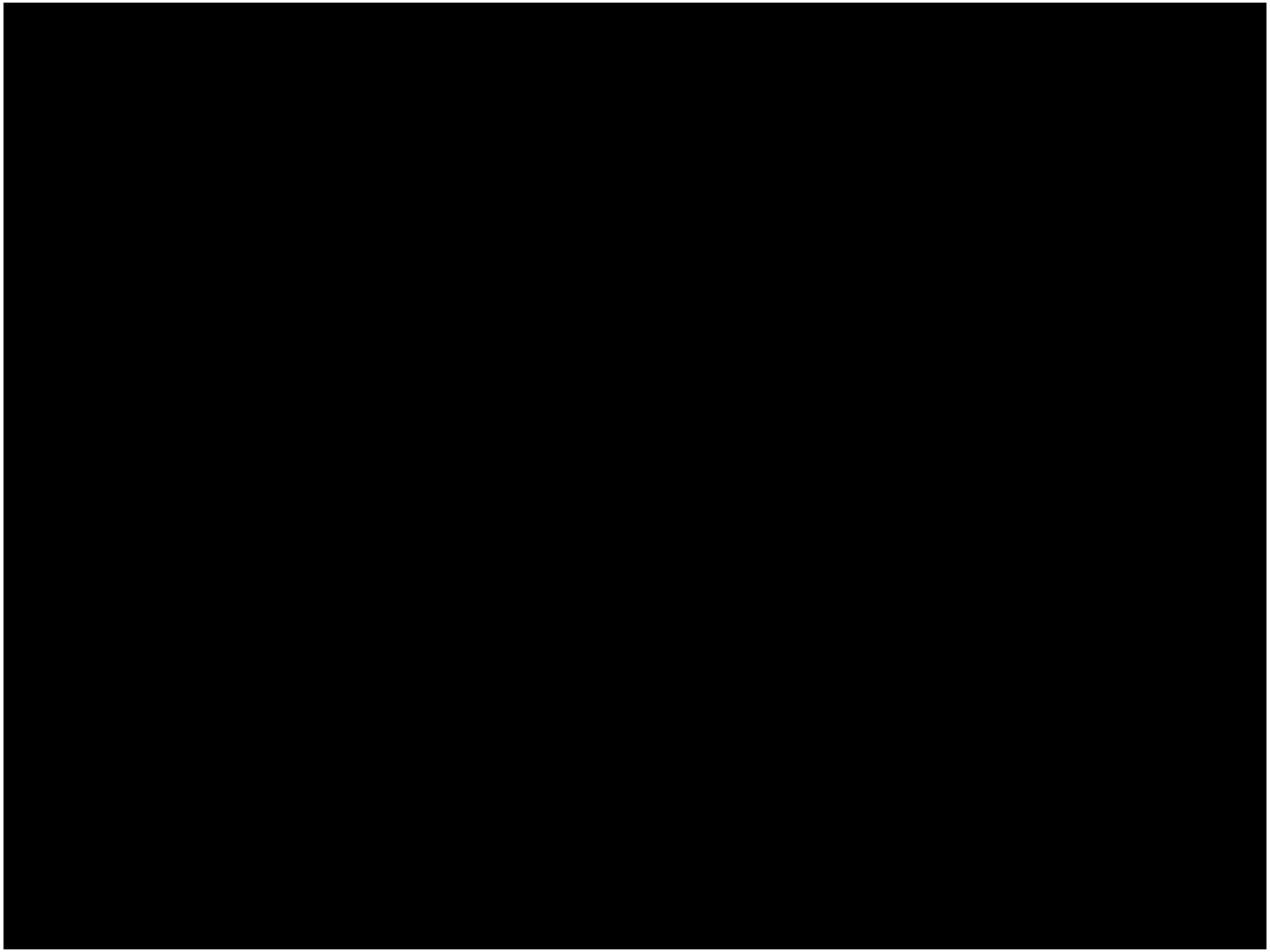
TRW

- TPF's deployment challenges can be met with TRW expertise and direct transfer and extensions of existing deployment technology
- TDRS
  - 8 systems
  - 45 elements
- TPF
  - 11 systems
  - 68 elements



TRW

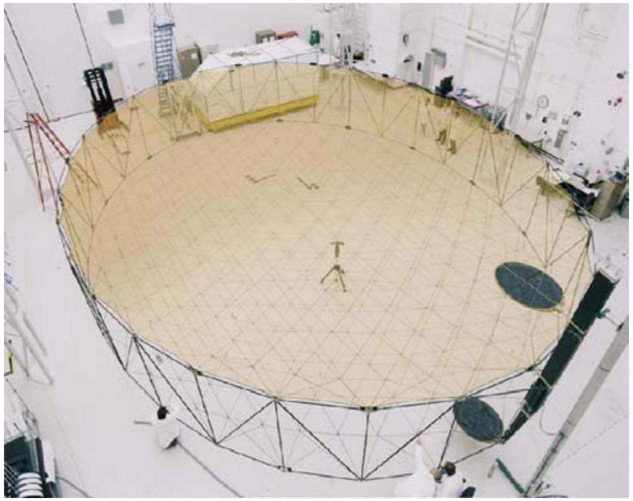
TDRS Deployment



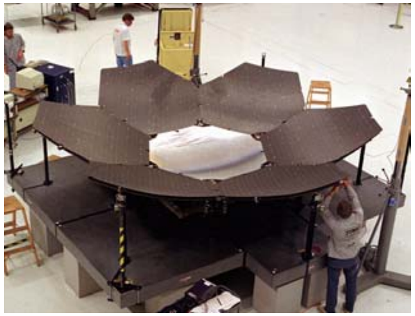
Continued Innovation and Advancement of Deployables

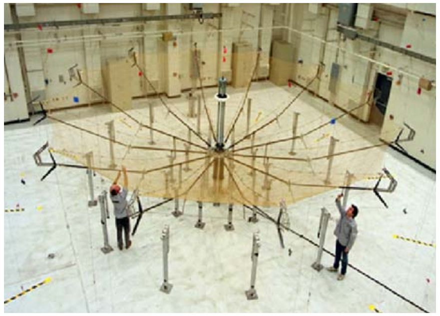
TRW

- TRW continues the tradition of innovation and development to meet future mission needs
  - Large apertures
  - Higher frequency
  - Lower cost
  - Lighter weight
  - Smaller packaging



12-m AstroMesh Thuraya Reflector





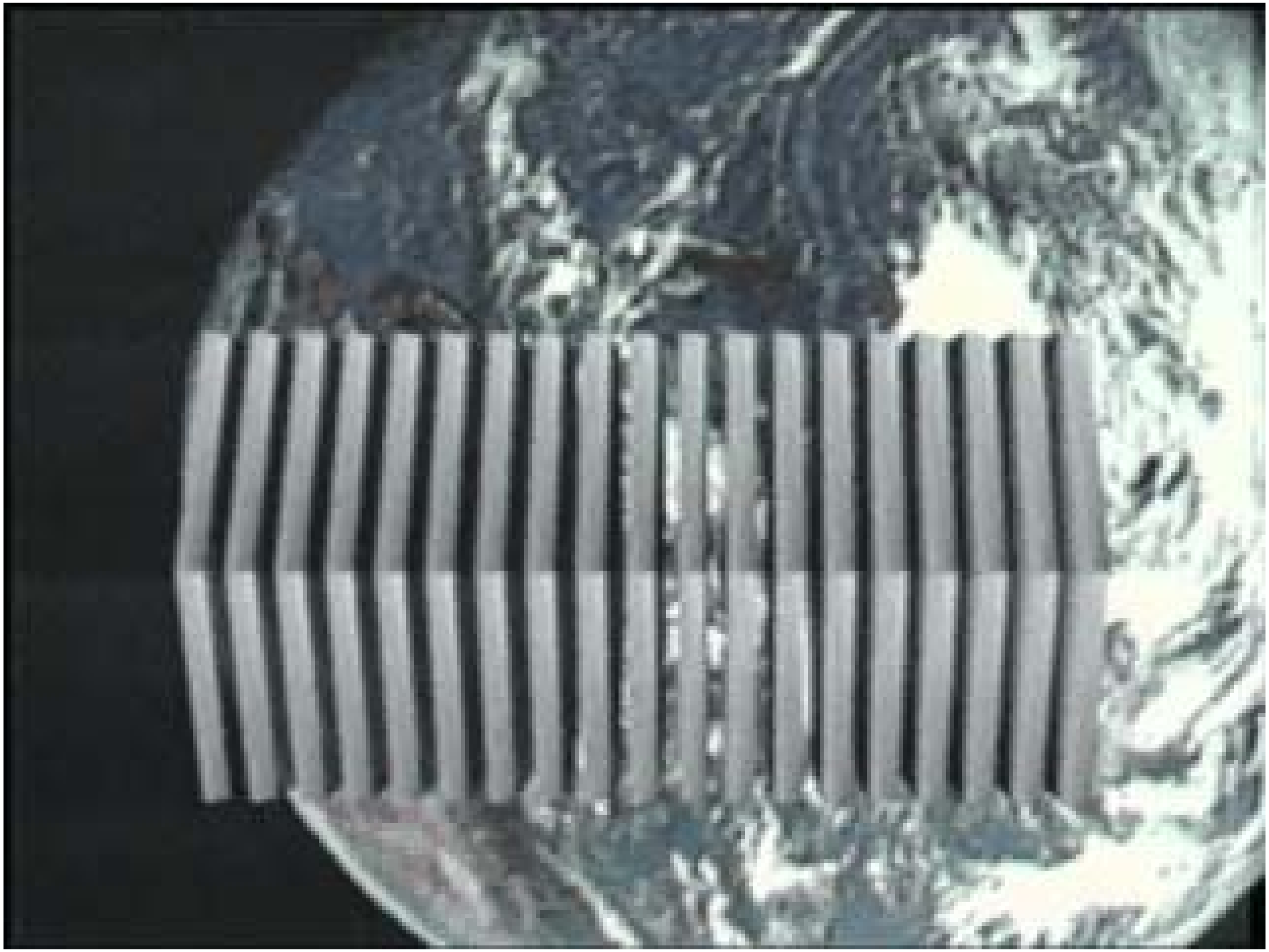
9.2-m PAMS Reflector

5-m PAMS Reflector

5-m HARD Reflector

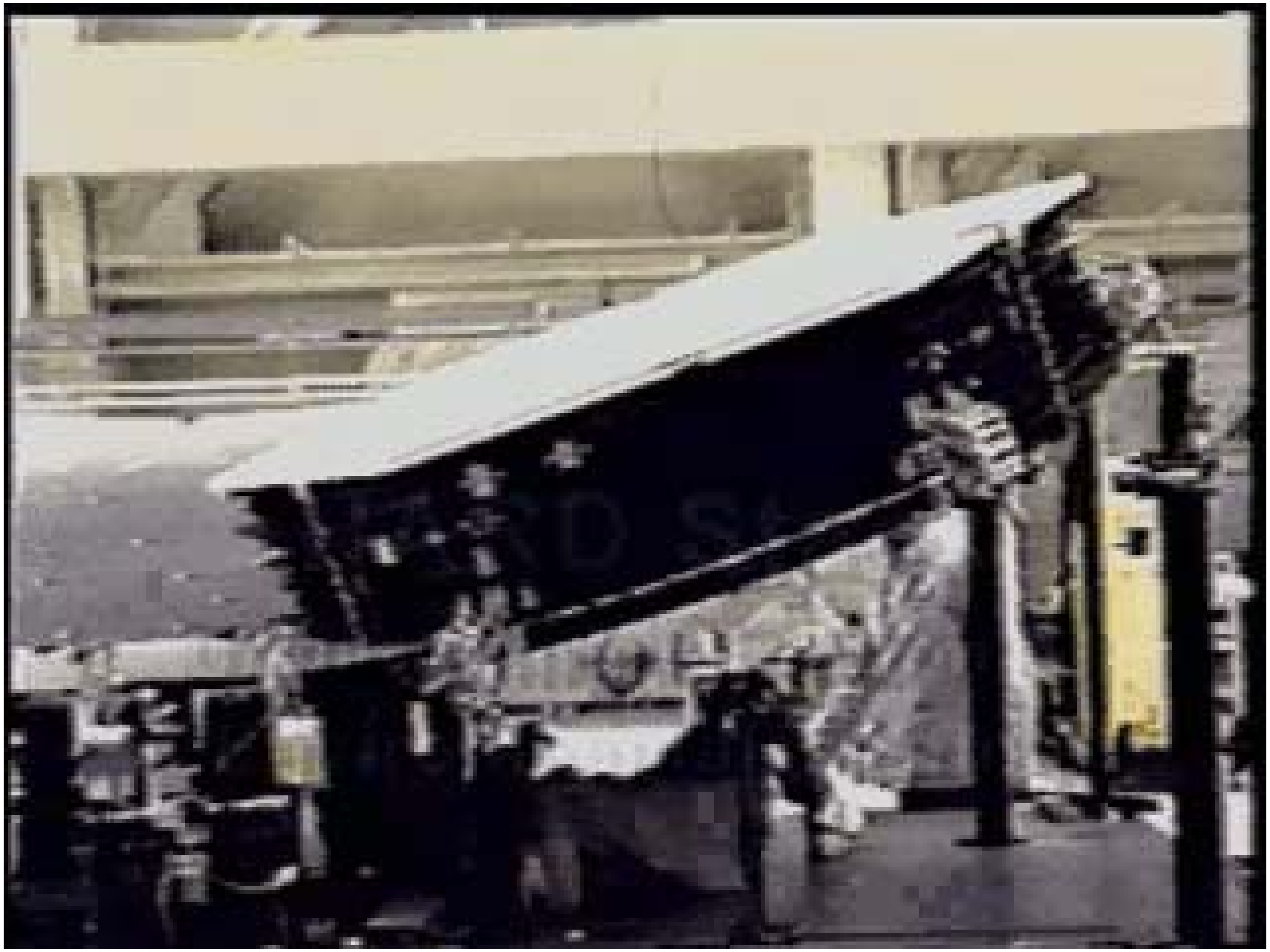
High Accuracy Reflector Deployment Concept

TRW



High Accuracy Reflector Development (HARD) Video

TRW



ACS Driving Requirements

- Pointing accuracy prior to Guide Star acquisition $\leq$ 10 arcsec, 1σ
  - Assures Guide Star appears within the fine guidance sensor FOV
- Pointing stability prior to Guide Star acquisition $\leq$ 1 arcsec, 1σ
  - Assures Guide Star image stability for acquisition
- Fine pointing accuracy with fine pointing control $\leq$ 0.003 arcsec, 1σ
  - Provides precision pointing of telescope LOS using fine guide sensor (FGS) and fine steering mirror (FSM)
- Maneuver time: 10 degrees slew in 60 minutes
  - Drives the selection of reaction wheels or control moment gyros

ACS Design Key Features

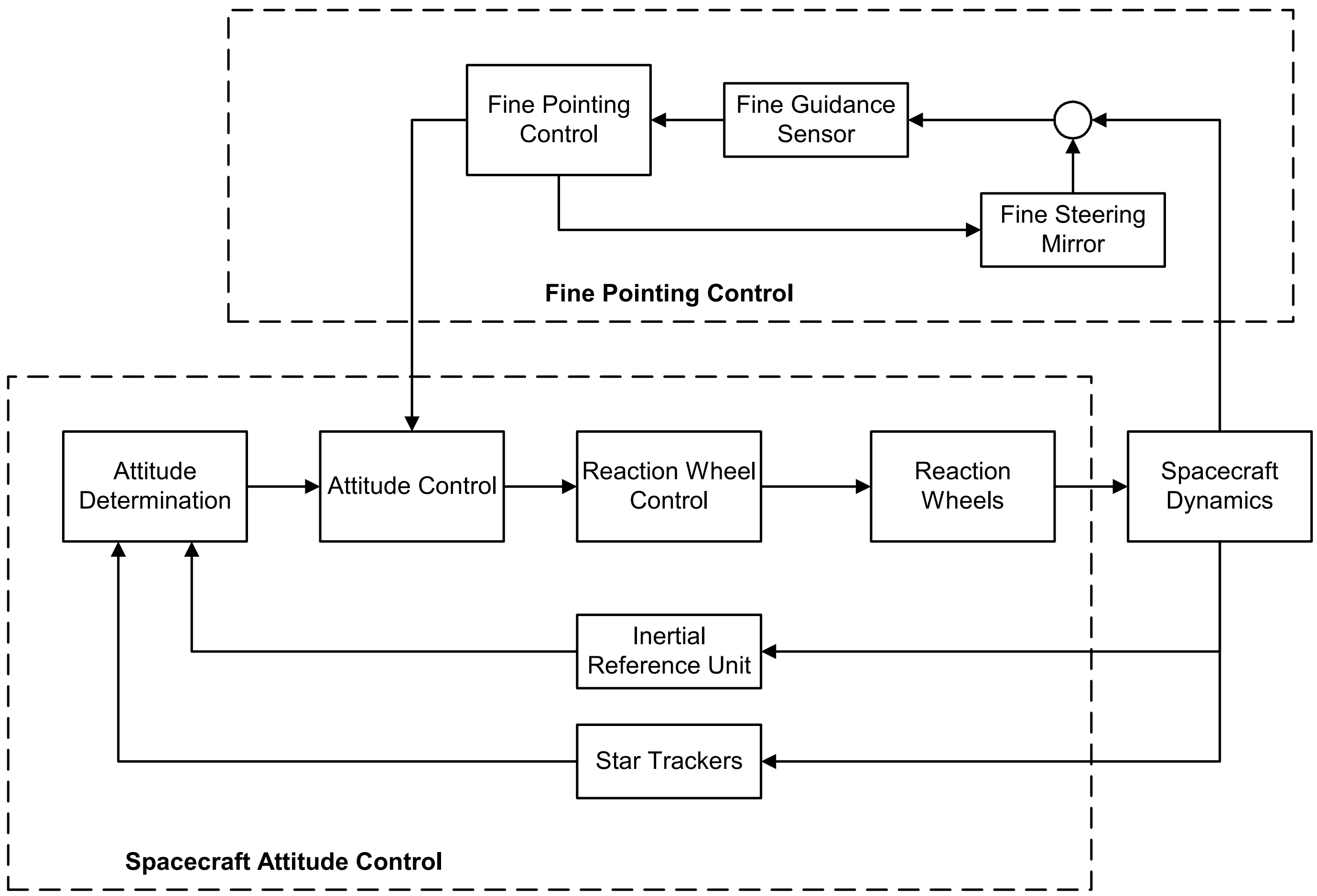
TRW

- Two-tier control architecture
  - IRU, star trackers, and reaction wheels provide spacecraft attitude maneuver and control with sufficient accuracy and stability for guide star acquisition
  - FGS and FSM system provides accurate telescope LOS pointing control
- Thrusters for ΔV and momentum unloading
- High gain antenna pointing control
- Vibration isolation for reaction wheel jitter reduction

ACS Functional Block Diagram

TRW

Attitude control system and fine pointing control system work in unison providing precision telescope pointing

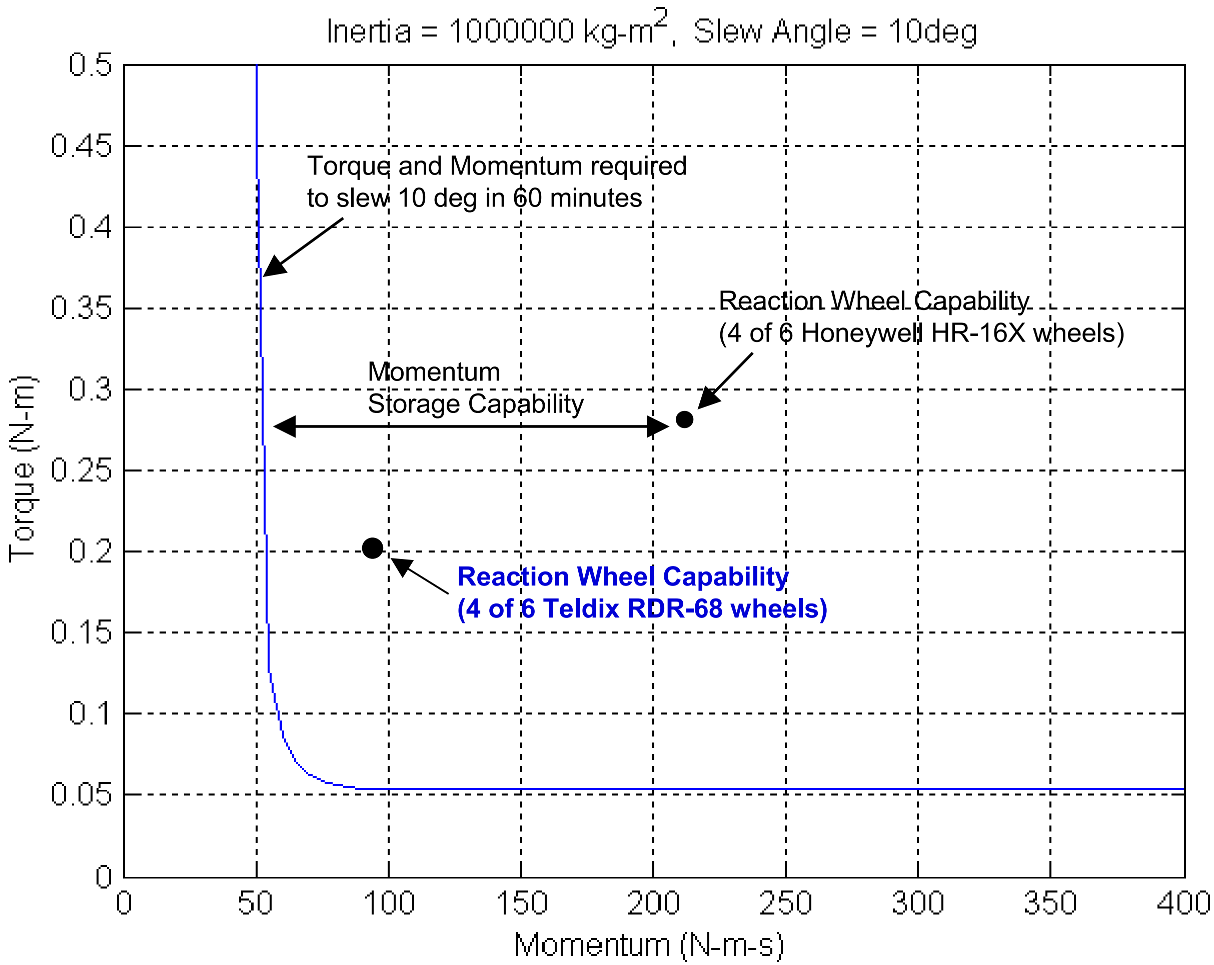


Reaction Wheels Provide Slew Capability

TRW

Four reaction wheels can slew the Observatory 10 degrees in 60 minutes

- Carry six wheels for redundancy



DMS Data Processing Flow

- Data processing is broken into three distinct functions
  - Focal plane
  - Payload
  - Spacecraft
- There are four thermal areas as shown
- IR Coronagraph, IR Camera, and NIR Imager integrate for 1000 seconds
- Guide camera has 60-second imaging time minimum during acquisition
- Each focal plane has output lines which reflect serial paths for pixels
  - For multiple lines the total pixels are uniformly divided

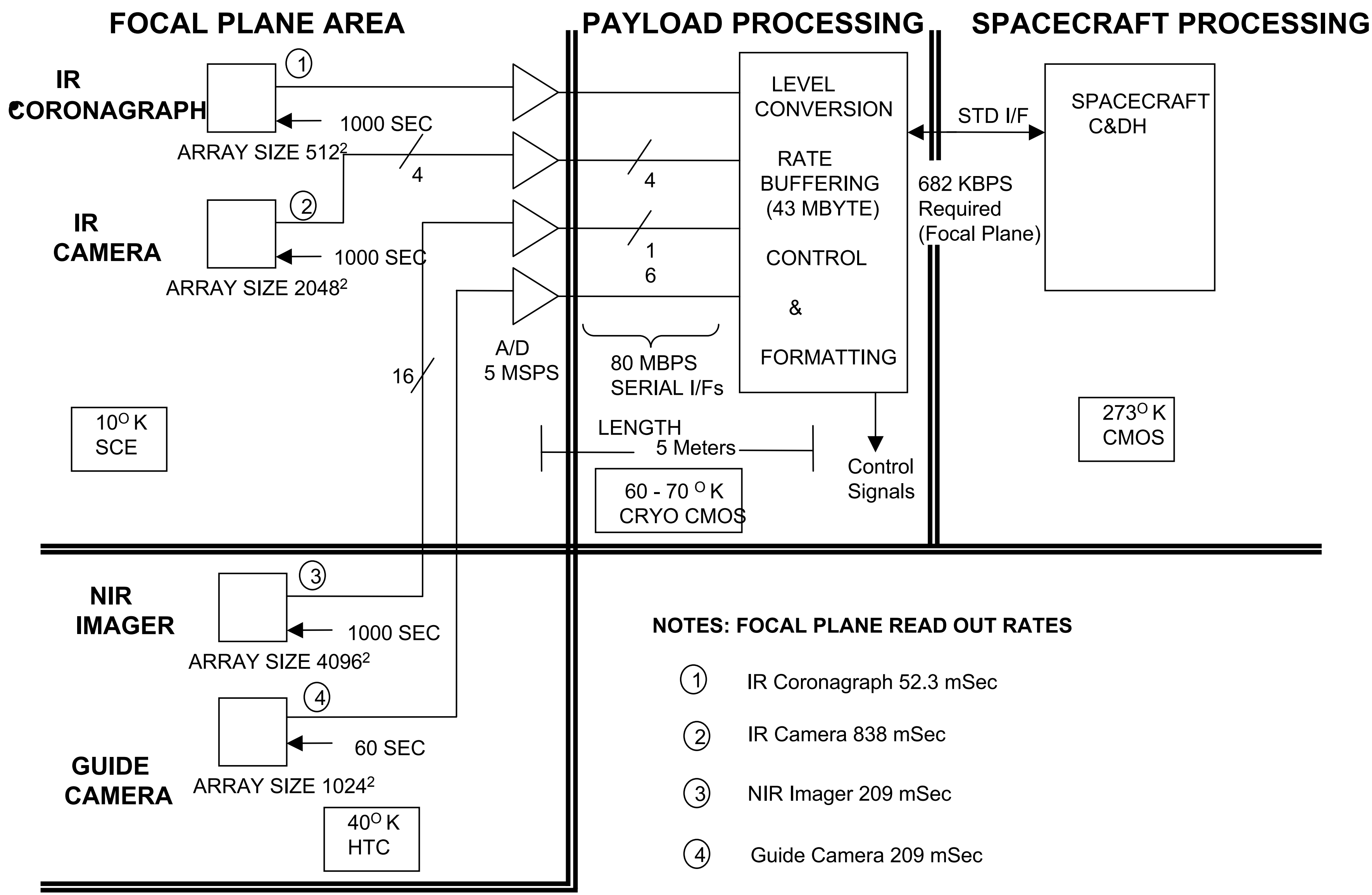
DMS Data Processing Flow

TRW

- A/D converters are SCE devices providing 16 bit quantization and serialization of data
  - Minimizes number of lines to payload processor
- Max transfer rate to payload processor is 80 MBPS based on A/D out put impedance
- Low voltage SCE serial digital data is sent to payload processing
  - One serial output per A/D converter
- Payload processing function provides four functions
  - Voltage level conversion provided for SCE to cryo; CMOS and cryo; and CMOS to standard CMOS levels
  - 80 MBPS serial data is buffered and rate converted averaging rate
    - Buffer size is based on full array of guide data and IR camera
  - Focal plane read out control and A/D converter control is provided
    - Only one focal plane and guide will be buffered at one time
    - Synchronous data transfer provided to payload processor
- First level data formatting provided mapping array to logical address
- Standard interface used to spacecraft C&DH
  - Due to rate conversion maximum rate required shall be less than 5 MBPS

DMS Data Processing Block Diagram

TRW



Payload Processing Function Requires Technology Development

TRW

- Industry survey indicates approx. 64 Kbit RAM represent demonstrated state of art
  - Density growth of at least 128 is needed
  - Growth must be provided with no power growth
    - Feature size is encouraging path for solution
    - Trades need to be performed
- Target power for entire payload processing function is 2 watts
  - Studies are needed to further define minimum power approaches
- Operating temperature for payload electronics needs further study and optimization

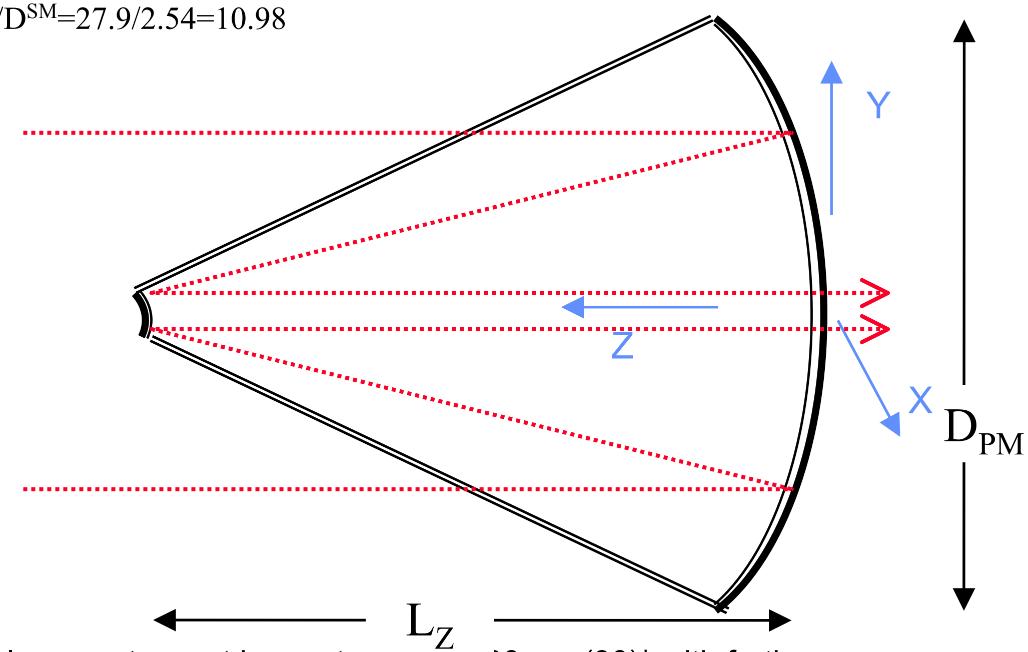
Optical Sensitivity to Displacements TRW

- A good approximation to LOS error is given by assuming an afocal telescope
- PM=primary, SM=secondary, IM=instrument module roof mirror
- Focal length, F^{PM}=33.21m = RoC/2 : (RoC=66.42m)
- L_z = distance from PM to SM = $F^{PM}(1 - 1/M)$ = 30.27 m
- M = magnification = 11.3 = $F^{PM}/(F^{PM} - L_z)$, also $M \sim D^{PM}/D^{SM} = 27.9/2.54 = 10.98$
- $f^{\#} = F^{PM}/D^{PM}$ = 33.21m/27.90m=1.193

$$LOS_X = -\frac{\theta_X^{IM}}{M} + \frac{2}{M}\theta_X^{SM} - 2\theta_X^{PM} - \frac{\Delta_Y^{SM} - \Delta_Y^{PM}}{F_{PM}}$$

$$LOS_Y = -\frac{\theta_Y^{IM}}{M} + \frac{2}{M}\theta_Y^{SM} - 2\theta_Y^{PM} + \frac{\Delta_X^{SM} - \Delta_X^{PM}}{F_{PM}}$$

$$\lambda_{\min} \approx 7\mu \Rightarrow \theta_{airy} \approx 2.44\frac{\lambda}{D_{PM}} = 130\text{mas}$$



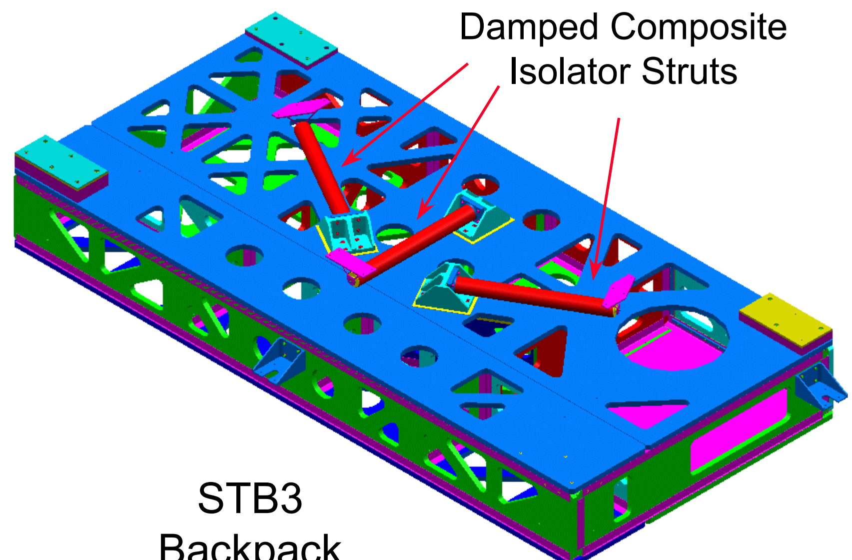
- Allowable WFE error at the PM is λ / 20 ⇒ PM displacements must be controlled to 300 nm (30)* with further downstream correction by deformable mirror
- Allowable total image motion is 6 mas (3) This implies that allowable displacements are:
- PM tilt = 3mas (1)   SM tilt=33 mas (16)   SM decenter= 1,000 nm (500)

- *** Dynamic allocation shown in ( )**

SIM Dual Stage Passive Vibration Isolation

First Stage at Wheel

- Spacecraft backpack houses six Teldix reaction wheels on Chandra-heritage vibration isolators at 7 Hz in rocking and 12 Hz in translation
  - SIM does not at present require damping in the optical payload
  - Low frequency vibrations are further rejected by active path length control at 100 Hz

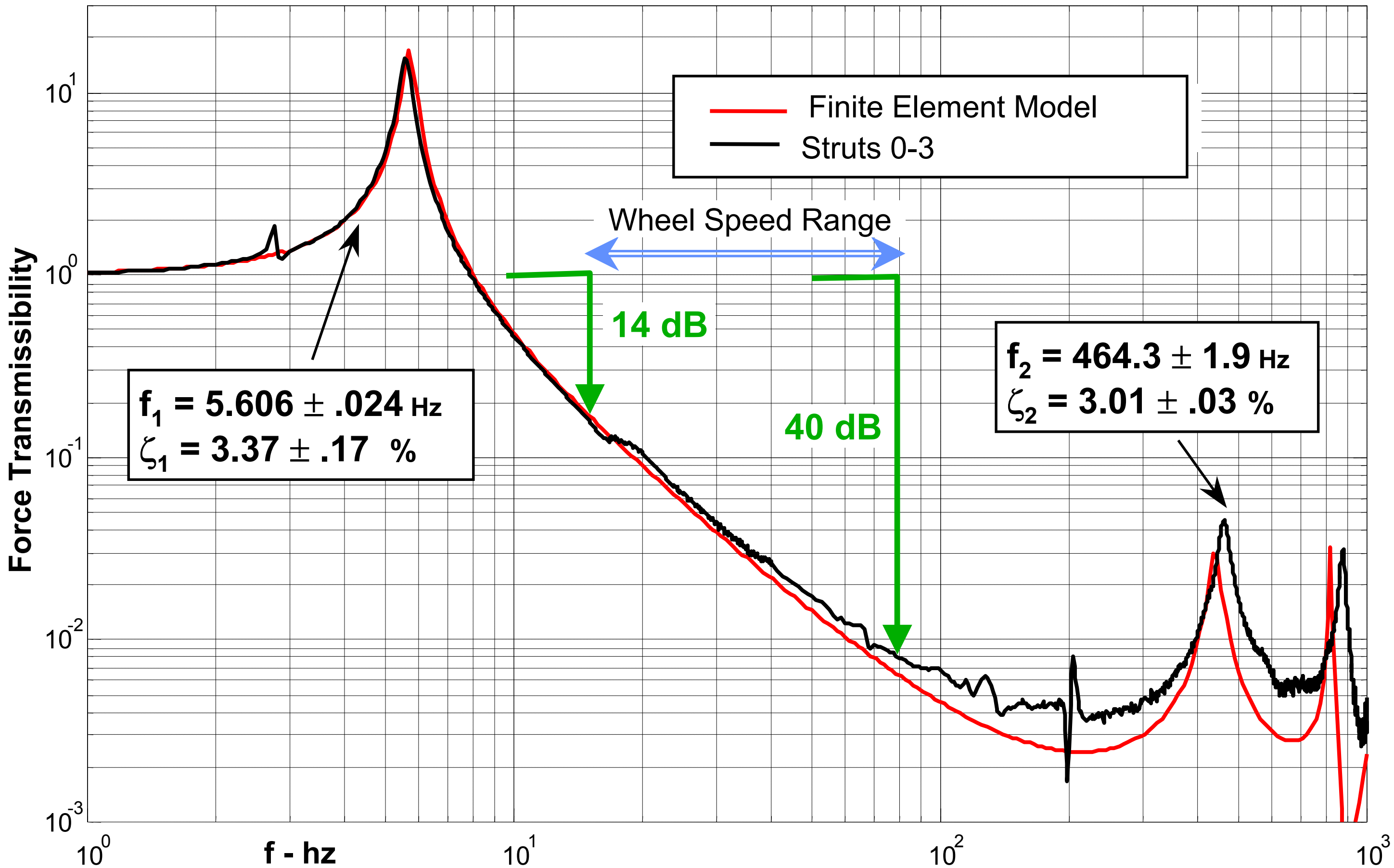


Second Stage at Backpack

- The spacecraft is isolated from residual backpack vibrations by a flexible kinematic mount composed of three damped beams with transverse “V”-flexures, transmitting only bending loads
  - No offload is required in 1G testing for 5 Hz struts

STB3 Beam Isolator Performance

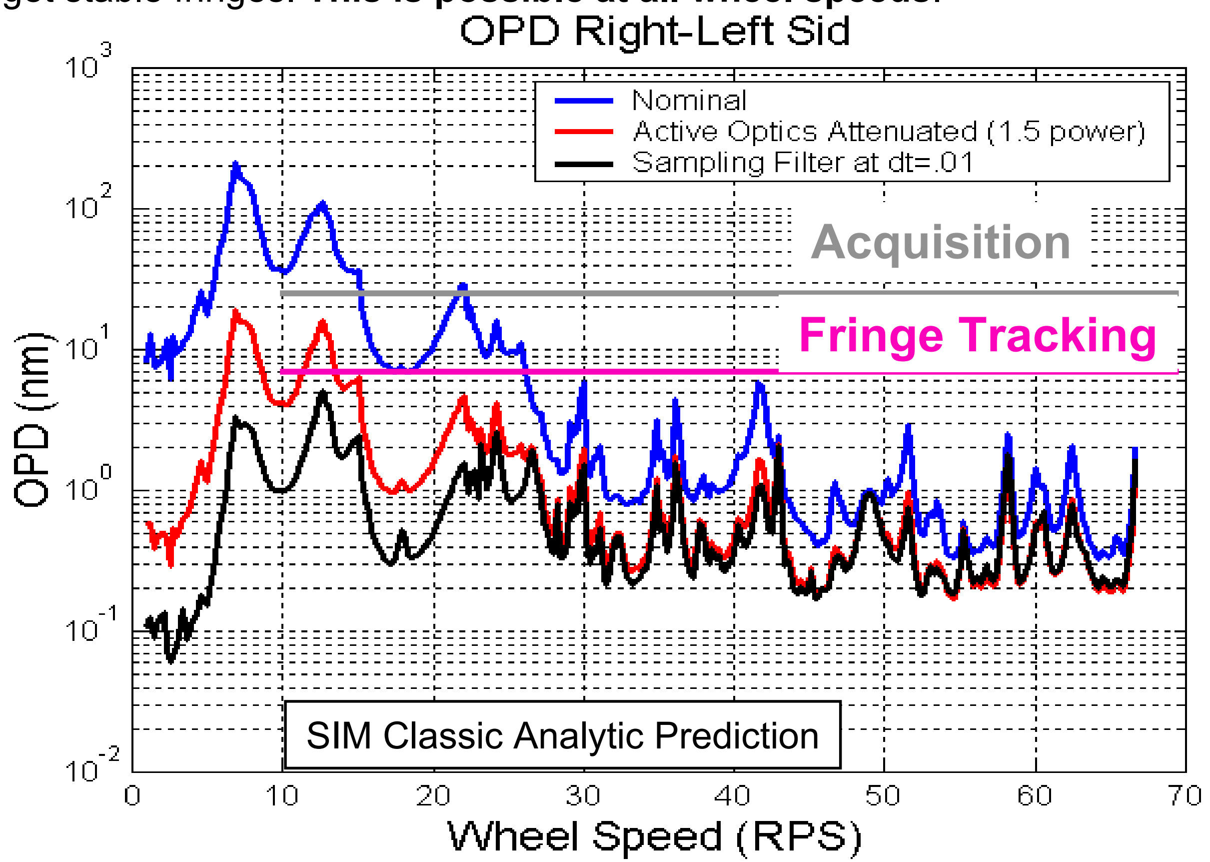
- Excellent match to FEM prediction and excellent repeatability
- Very little high frequency dynamics due to wave absorption feature
- Better attenuation could be attained at low end of wheel speed range by softening strut to 1-2 Hz, at expense of adding offload for 1G testing



SIM Dynamic Stability Performance

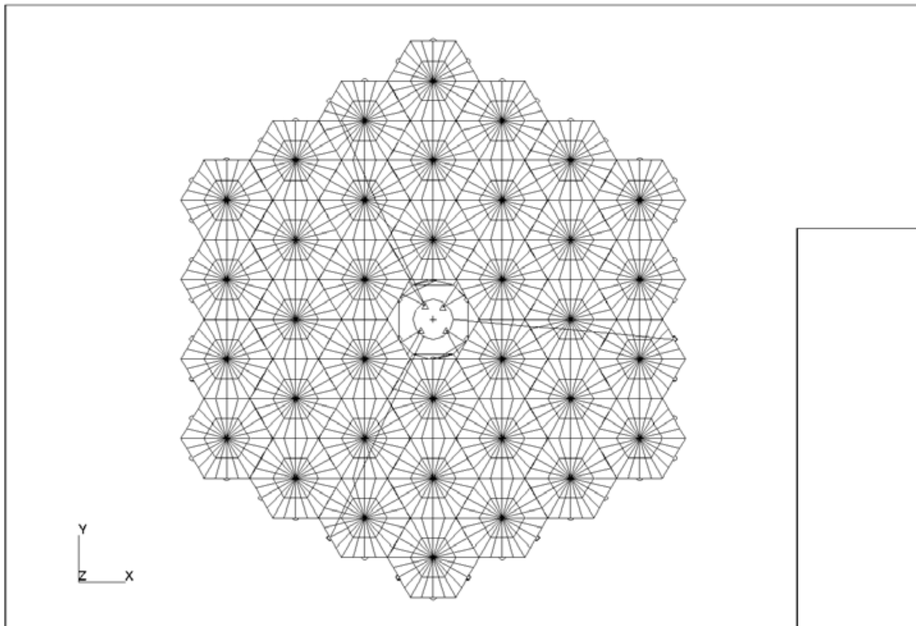
TRW

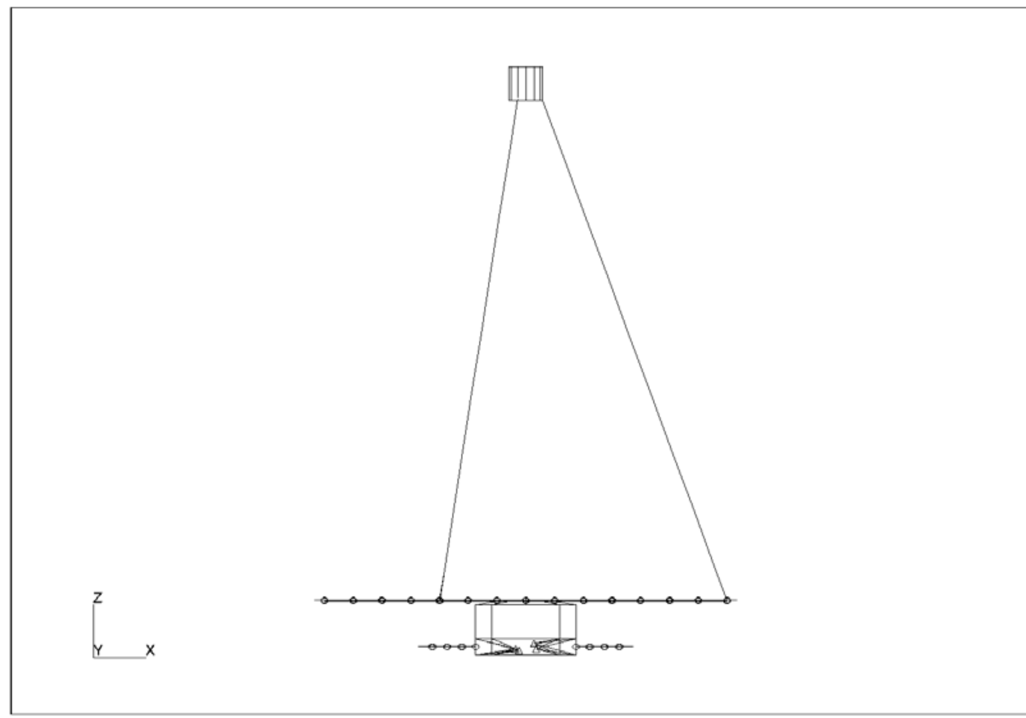
– Nominal is raw optical path difference due to Teldix reaction wheel disturbance with **7.5 Hz backpack isolator and 7-12 Hz Chandra wheel isolators**.
– **In fringe tracking mode** a 100 Hz path length control loop attenuates low frequency response. **The 6 nm allocation is met if wheels spin above 15 rev/second**
– **In acquisition mode** the fringes must lock on within a 10 msec window. Motion must be less than 25 nm to get stable fringes. **This is possible at all wheel speeds**.



Dynamic Modeling Demonstrates Feasibility

TRW





Overall Response Levels

TRW

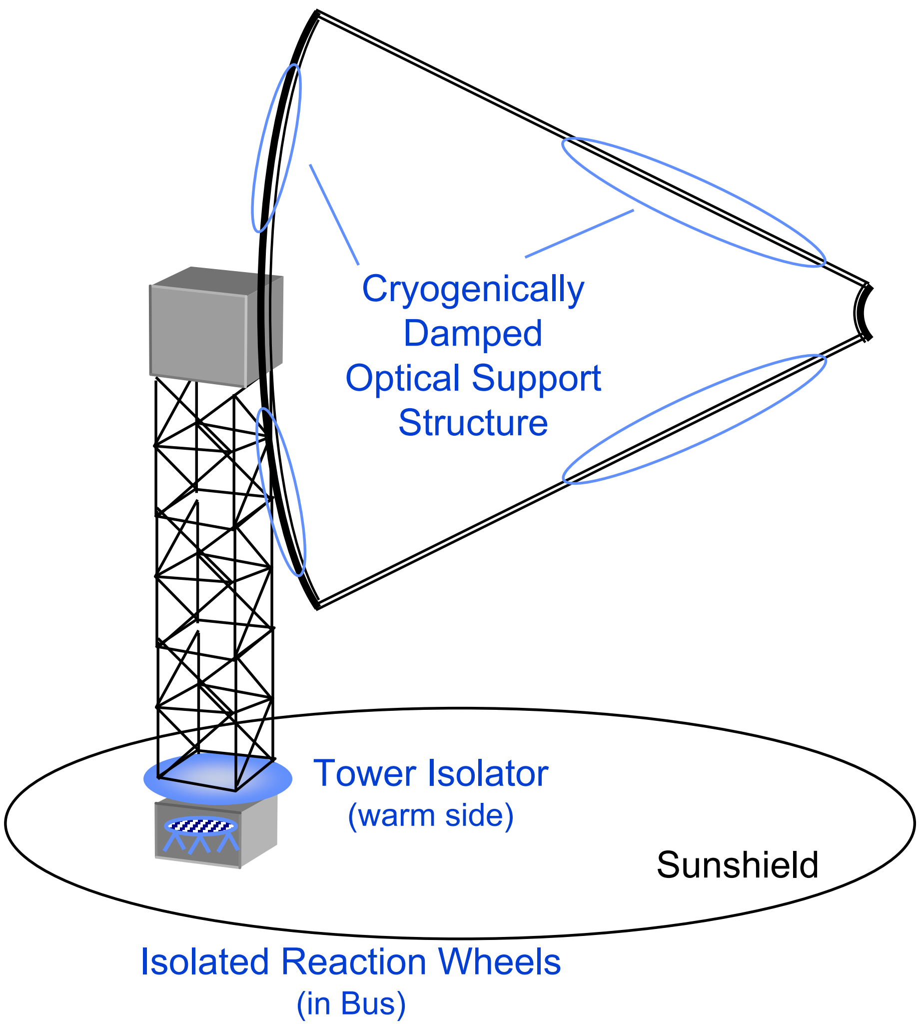
- Hard-mounted RWAs
  - 583 nm (primary mirror piston)
  - 128/109 mas (primary mirror tip/tilt)
  - 128/109 mas (secondary mirror)
  - 0.37 arcsec (primary mirror alignment)
  - 0.73 arcsec (secondary mirror alignment)
- Isolated RWAs (Chandra/SIM isolation scheme}
  - In-work nm (primary mirror piston)
  - In-work mas (primary mirror tip/tilt)
  - In-work nm (secondary mirror)
  - In-work arcsec (primary mirror alignment)
  - In-work arcsec (secondary mirror alignment)

TPF Vibration Control Technology Roadmap

TRW

- Due to its large size TPF will have fundamental vibration modes well below 10 Hz
  - Some modes may interact with the vibration isolator
  - An active loop in the isolator will enhance suppression of low-mid frequency structural interactions
  - Passive isolation will reject mid-high frequency vibrations
- For 6th-7th magnitude stars, sufficient photons reflect from the occulting spot back onto the quad-cell detector to sustain 1000 samples per second
  - Allows a fine steering mirror loop at 100 Hz bandwidth
  - Vibratory line of sight perturbations are thus not a major concern
- Defocus and other wave front errors cause the point spread function to leak around the occulting spot
  - The deformable mirror corrects quasi-static wave front errors.
  - Vibratory wave front errors must be suppressed using isolation, stiffening and damping

TPF Multi-Layer Vibration Control

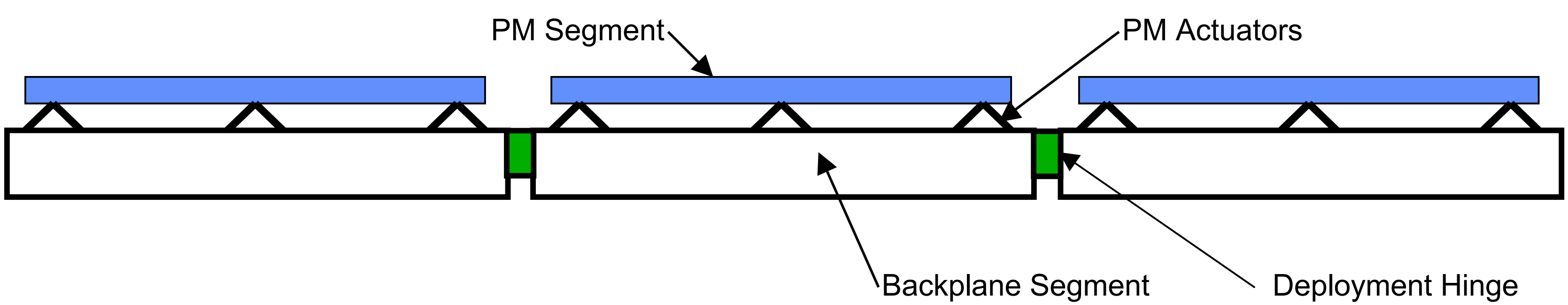


- 1st Isolation layer is passive at the wheel
  - Chandra build to print
- 2nd Isolation layer is passive with active augmentation at the bus-tower interface
  - Passive 1-2 Hz isolation with viscoelastic damping (SIM heritage)
  - Attenuates residual wheel vibrations transmitted to bus and any unforeseen vibrations in the bus
  - Active augmentation provides additional suppression of low-frequency vibrations
  - Characterization of micro-Newton force sensor is still required at low frequency and low vibration levels.
- Cryogenic damping in telescope structure limits dynamic amplification.
  - Prefer passive damping
  - Room temperature operation desirable
  - Undamped cryogenic structures can have damping as low as 0.002%

TPF Thermal Control Scheme

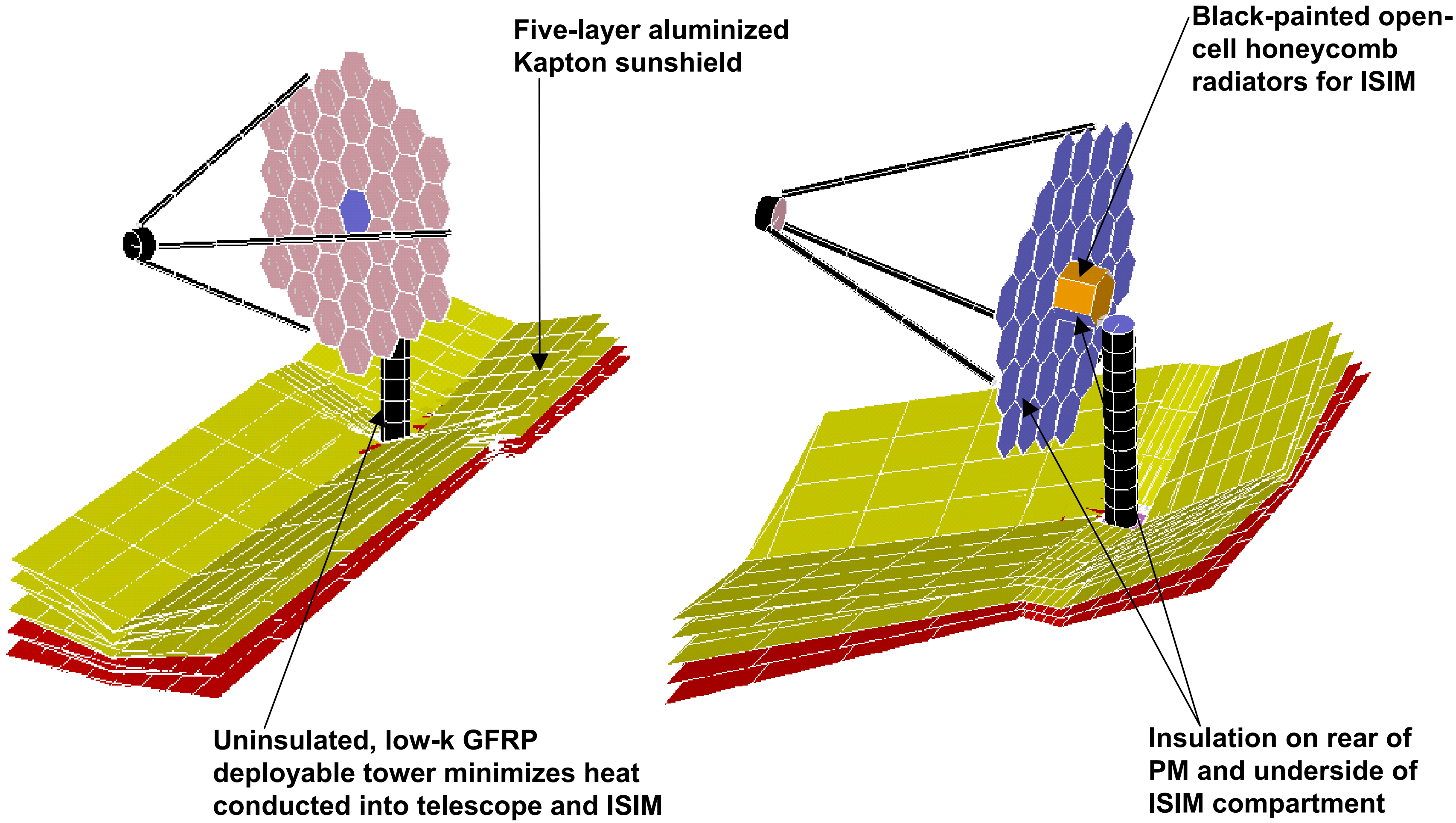
TRW

- Sunshield ensures that no sunlight impinges on cryogenic telescope or ISIM
  - five membrane layers with sun-facing layer measuring 58 m x 30 m
  - shape will be selected to balance solar pressure-induced torque; i.e., center of pressure passes very near observatory center-of-gravity
- Telescope supported off bus using deployable tower with low-thermal-conductivity graphite structural members
- Each hexagonal mirror element and its associated back plane structure are insulated from the warmer sunshield and are isolated from adjacent mirror segments



TPF Thermal Control Scheme Showing TSS Thermal Model

TRW



Thermal Design Requirements vs. Capabilities

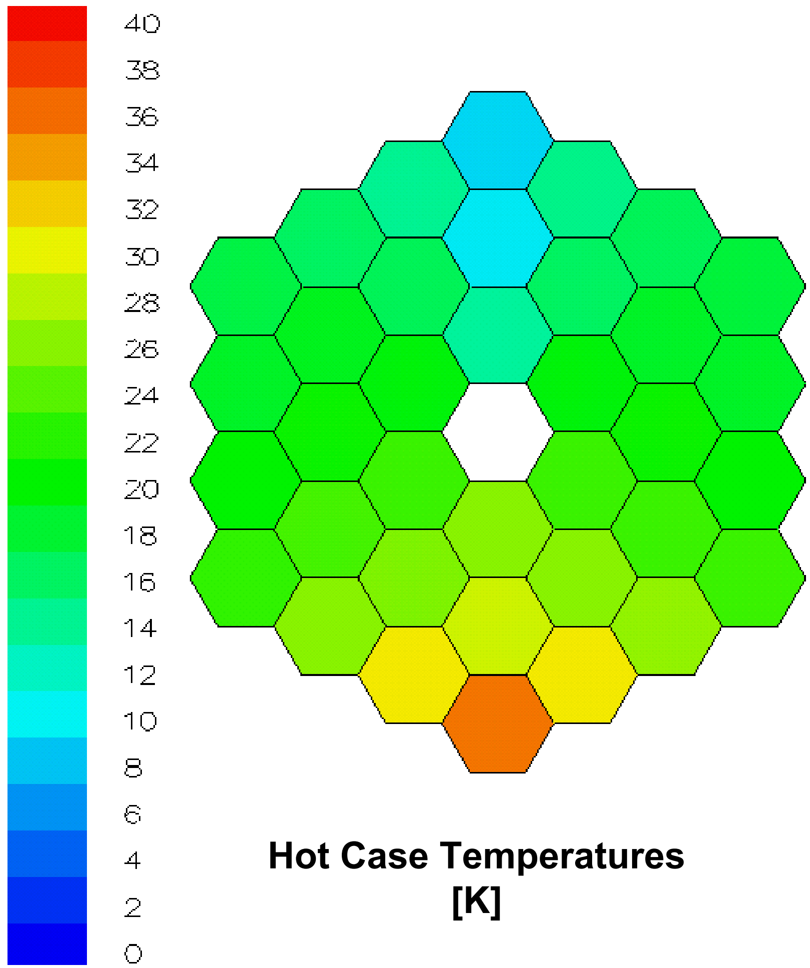
TRW

Design Parameter	Requirement	Capability
Maximum Temperature of Primary Mirror Elements	< 70 K	21 K average 35 K maximum
Maximum Hot-to-Cold ΔT of Primary Mirror Elements	< 1.0 K	0.24 K average 0.33 K maximum
Maximum Temperature of Secondary Mirror	< 70 K	25 K
Maximum Hot-to-Cold ΔT of Secondary Mirror Support Struts	< 1.0 K	0.11 K minimum 0.15 K maximum
ISIM Temperature	< 30 K	Can reject 0.62 W with radiator @ 30 K

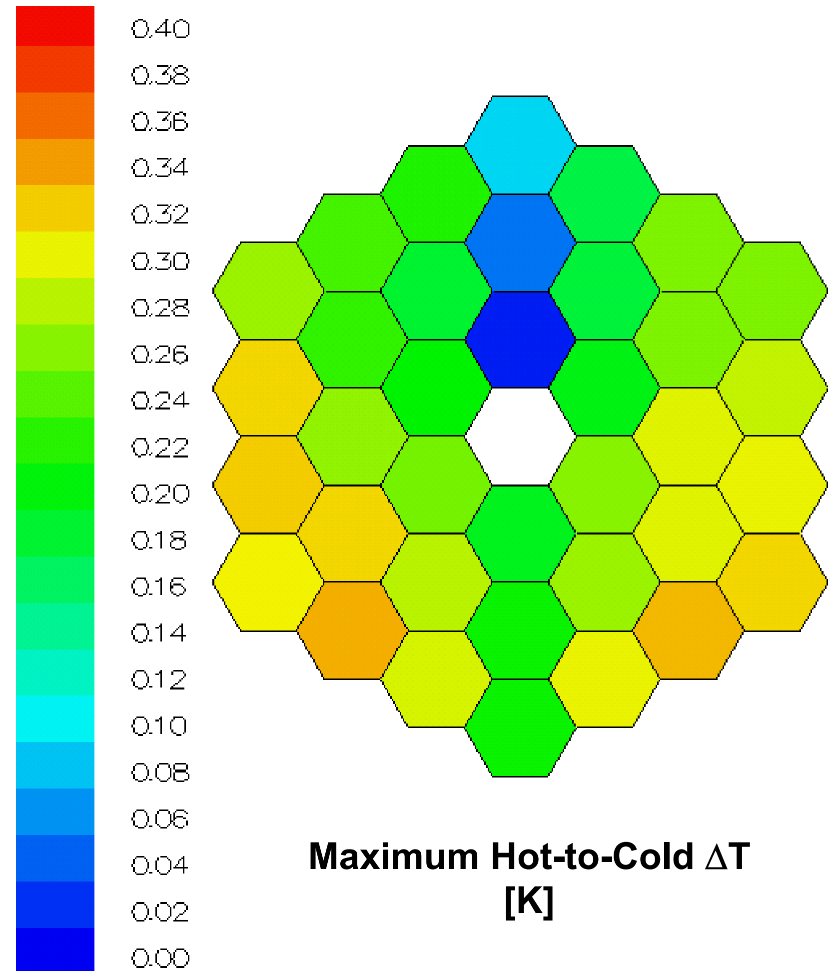
TRW's passive TPF thermal design satisfies all key thermal requirements and builds upon IR&D thermal vacuum testing of our sunshield design approach

Bulk Temperature and Thermal Stability of TPF Primary Mirror Elements

TRW



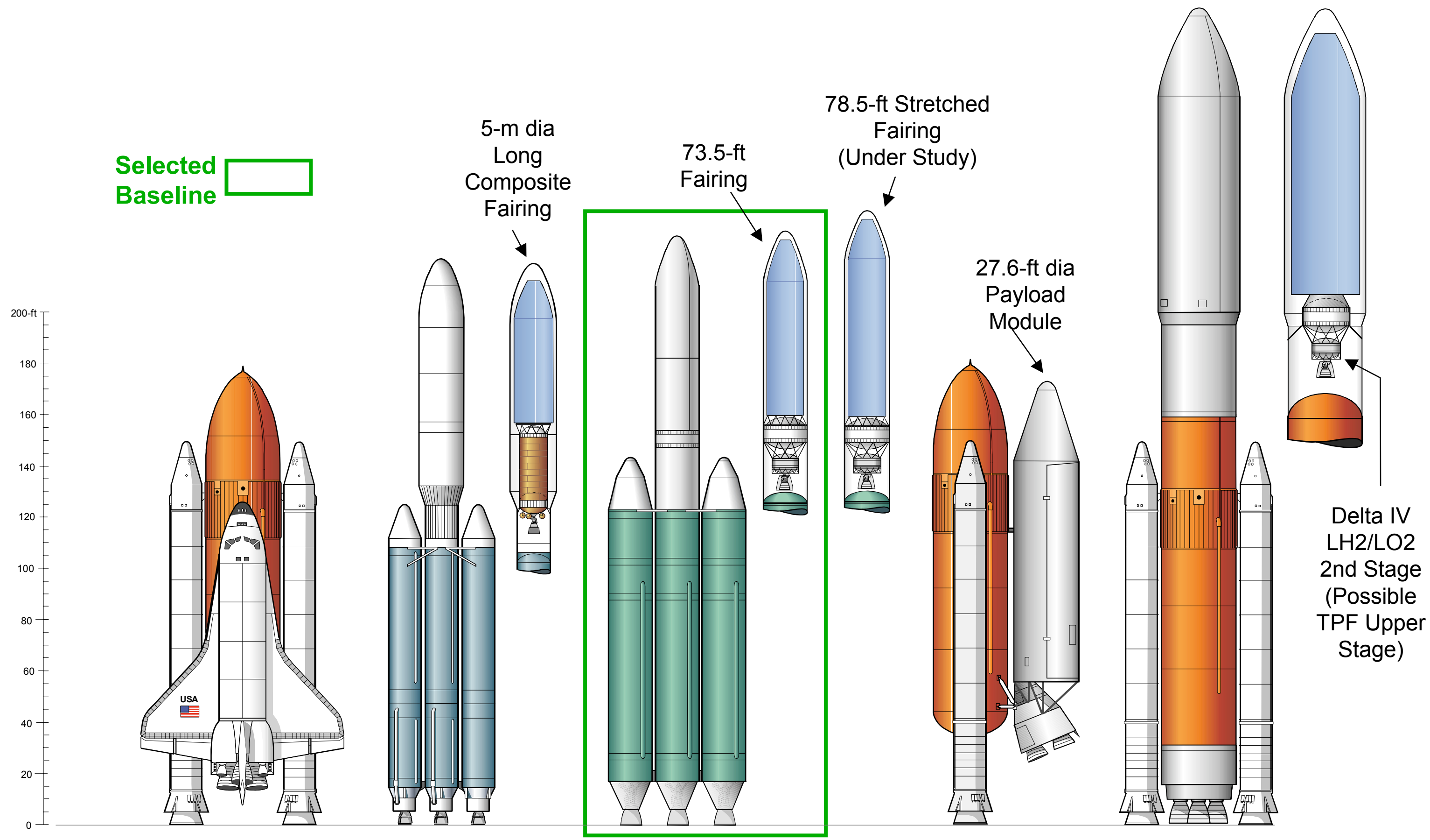
Hot Case Temperatures [K]



Maximum Hot-to-Cold ΔT [K]

TPF Candidate Launch Systems

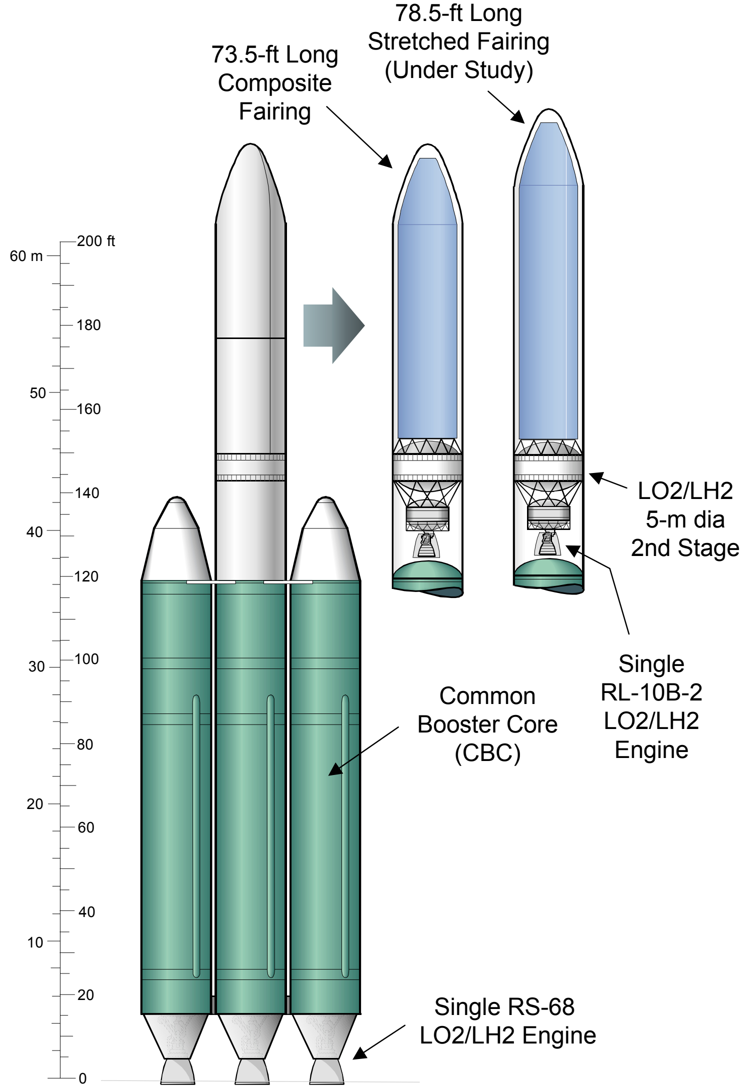
TRW



	Shuttle	Atlas V Heavy	Delta IV Heavy	Shuttle-C	Magnum
Envelope	4.57 x 18.29 m *(Full Bay)*	4.57 x 16.60 m	4.57 x 19.74 m	7.6 x 21.9 m	7.6 x 28 m
L2 Capability		10,300 kg	9,700 kg	11,000 kg (3)	>21,000 kg (4)
Status	N/A (1) Operational	Development (2)	Development; 2003 1st Flt	Concept	Concept

(1) ~5500 kg L2 Capability with new Storable Stage
(2) EELV development thru CDR; No firm orders
(3) Using new biprop stage sized for TPF
(4) Using Delta IV 5-m LH2/LO2 Stage

Delta IV Heavy



Vehicle Description:

- Strap-On's: 2 x Common Booster Cores
- Core Stage: Common Booster Core with Al isogrid tanks and single RS-68 LO2/LH2 engine
- Upper Stage : 5-m dia LO2/LH2 Stage with single RL10B-2 engine
- Payload Fairing : 5-m dia 73.5-ft Composite (Single Payload derivative of 73.5-ft Dual Payload Fairing)
- Payload Envelope : 4.57 x 19.7 m (15.0 x 64.8-ft)

Capability:

- Launch Site : CCAS SLC-37
- LEO Capability : 23,060 kg into 200 km at 28.5 deg
- L2 Capability : ~9,700 kg *(Direct Inject with 2nd Stage)*

Programmatic:

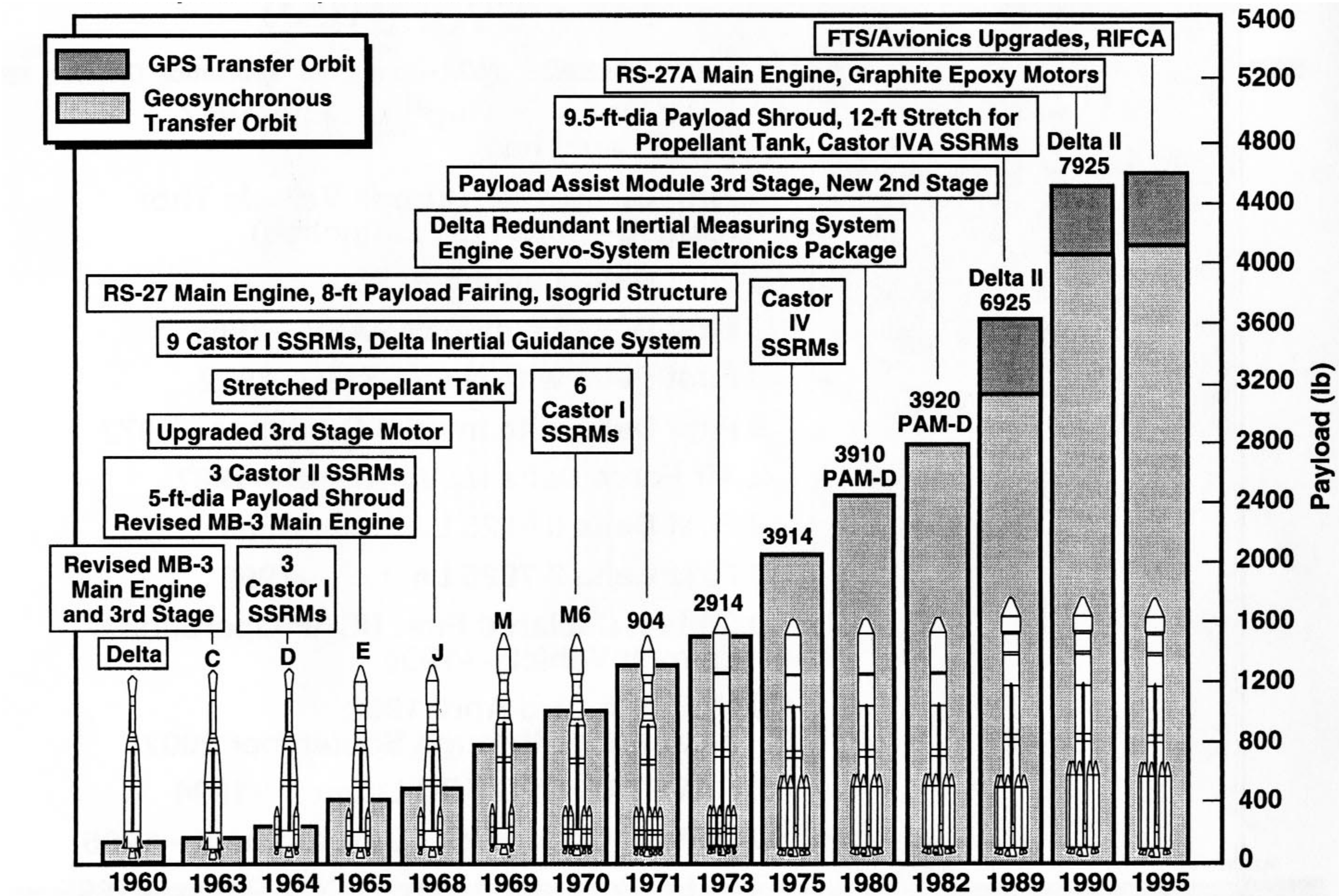
- Status: EELV Program Development - 1st Flight for Heavy version Planned for 2003
- Recurring cost per flight : ~$150-170

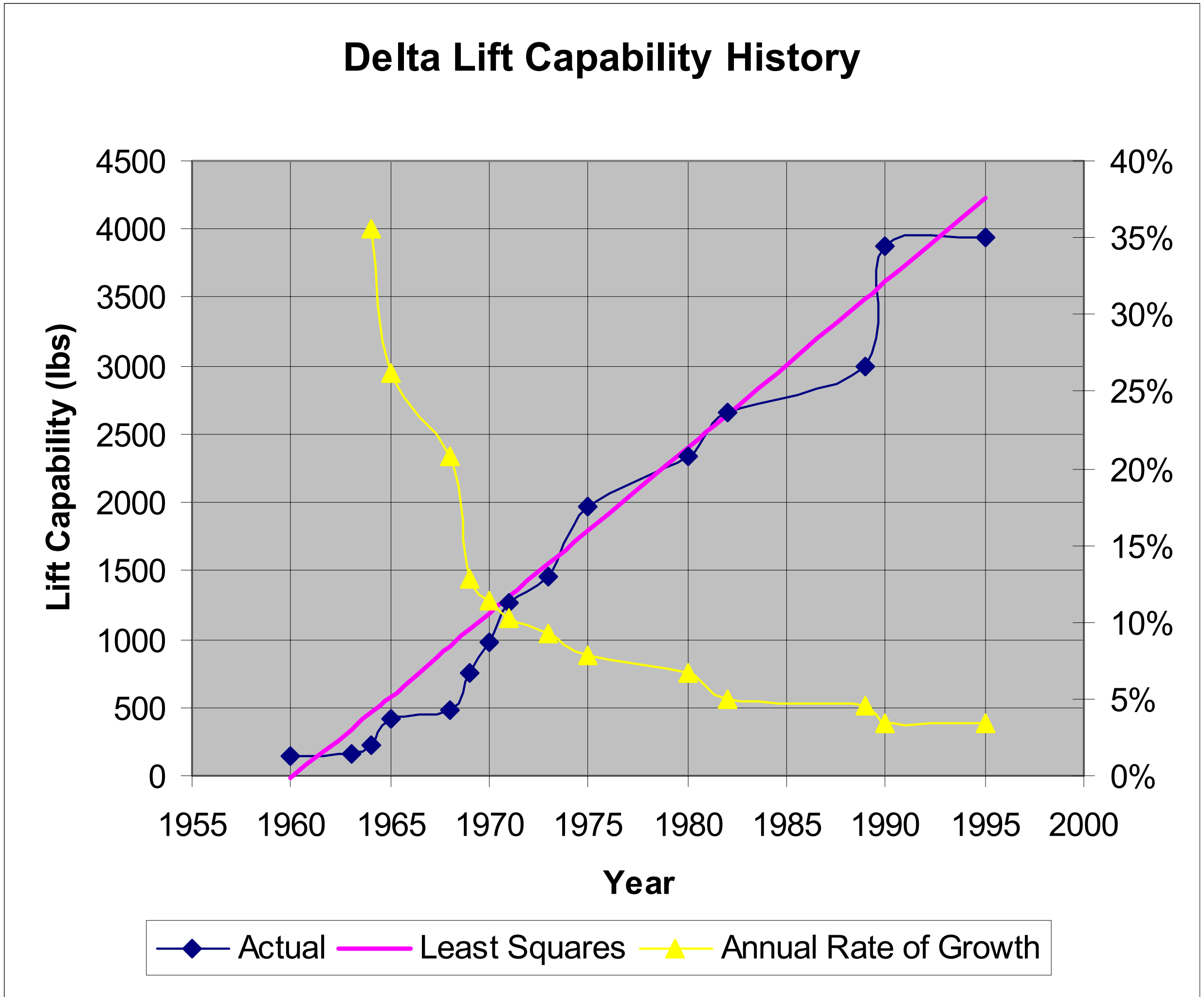
Remarks:

- 5-m Fairing stretch up to 78.5-ft length under study
- Studies currently examining potential vehicle performance upgrades over next decade

Growth with Enhanced Operability and Reliability

TRW

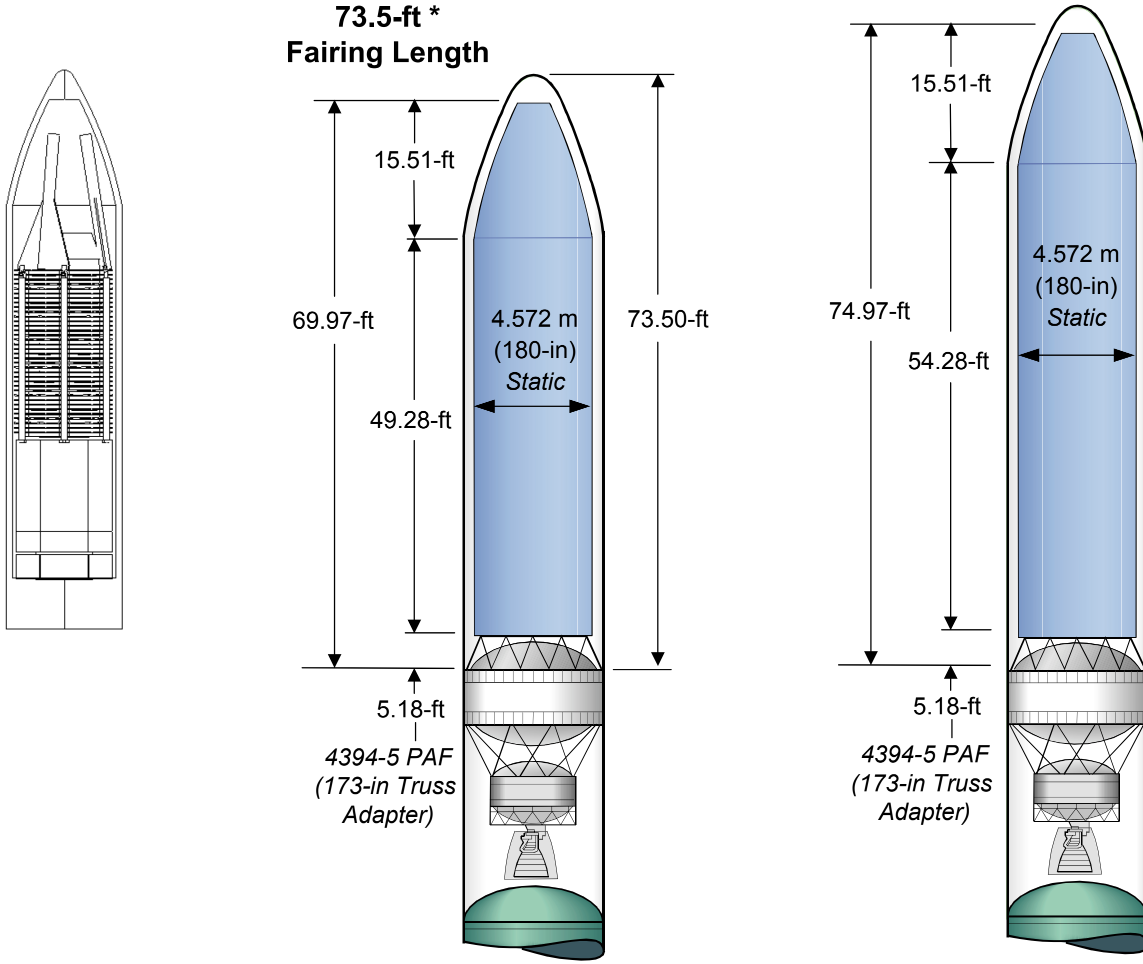




- Delta II Lift Capability has grown at a rate of 4-5% annually since 1980
- Atlas, Titan and Ariane have shown similar growth rates.
- 1% per year for the Delta IV Heavy would be sufficient for TPF

Delta IV Heavy 5-m Fairings

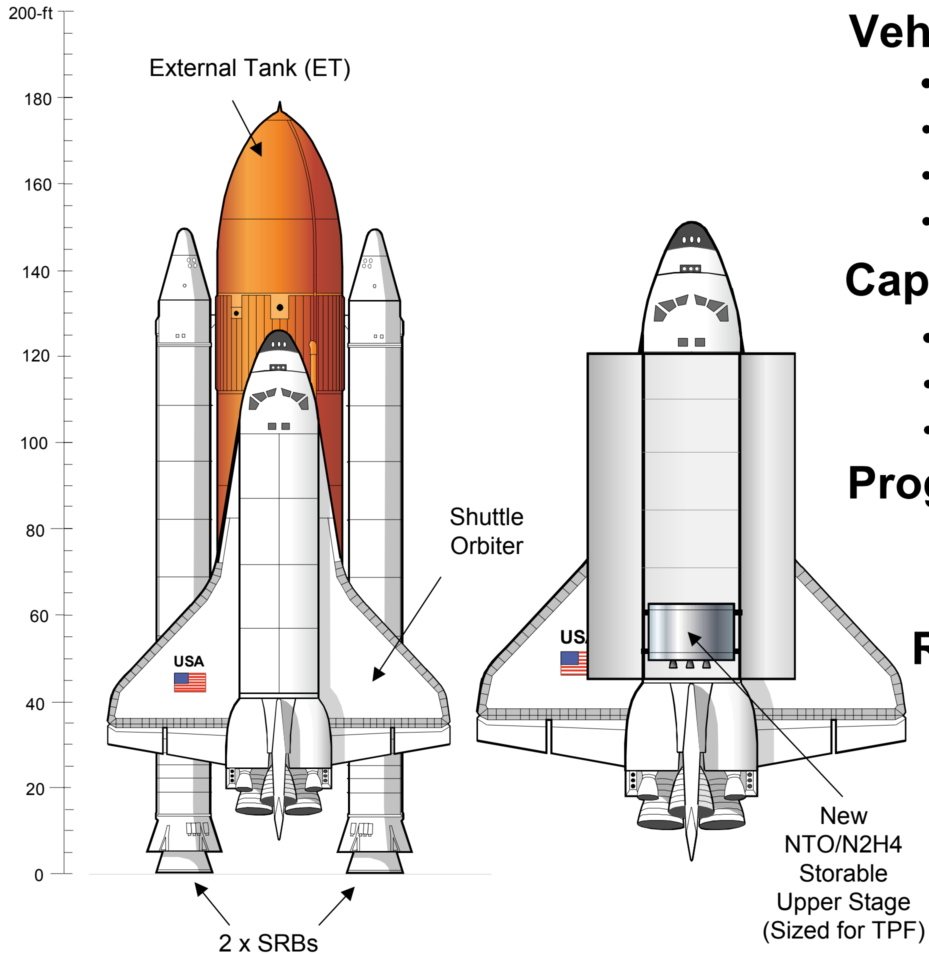
TRW



86-ft was Maximum Fairing Length Examined

** Based on 73.5-ft Dual Manifest Payload Fairing/Canister Design shown in Delta IV Payload Planner's Guide*

Space Transportation System



Vehicle Description:

- Strap-On's: 2 Segmented SRBs
- Core Stage: ET and Orbiter with 3 SSMEs
- Upper Stage: TBD (New Storable Stage shown)
- Payload Bay: 4.57 x 18.3 m (15 x 60-ft) (Full Bay)

Capability:

- Launch Site: KSC Pad 39A/B
- LEO Capability: 22,675 kg into 160 nm at 28.5^{o}
- L2 Capability: ~5500 kg (using Storable Stage)

Programmatic:

- Fleet of 4 Shuttles Operational
- Recurring cost per flight: \$90-\$300M (1)

Remarks:

- Available payload bay length for Shuttles with air locks is 47-ft (14.3-m);
- Columbia Orbiter not fitted with air lock and has 5,000 lbm lower LEO capability

(1) Launch cost estimates from "International Reference Guide for Space Launch Systems", 3rd Edition excluding upper stage and ASE. The \$90M is marginal cost of adding additional flight to planned manifest. NASA could also provide unmanifested Shuttle flight to TPF Program at no flight cost.

Launch Vehicle Summary

TRW

- **Delta IV Heavy launch vehicle baseline for TPF**
  - Delta IV vehicle in development with 1st planned Heavy flight in 2003
  - 73.5-ft Long 5-m fairing (based on 73.5-ft Dual-Manifest Fairing) provides adequate envelope for TPF
  - Fairing lengths to 78.5-ft currently under study
  - Delta IV 2nd Stage directly injects TPF into L2 transfer orbit (no new upper stage needed)
  - Current L2 direct inject capability of ~9700 kg expected to increase with performance upgrades over next decade
- **Atlas V Heavy being developed through CDR under EELV program but no production orders currently exist**
  - Fairing envelope length slightly shorter than for Delta IV
- **Magnum and Shuttle-C Launches offer increased envelope diameters and throw-weight but NRE development costs are high and availability in 2015 uncertain**
- **Single Shuttle mission does not provide needed performance to L2**

Summary

TRW

- Spacecraft technologies needed for the coronagraph architecture are direct evolutions of pre-TPF missions (SIM, NGST…)
- Technology roadmap activities
  - Vibration control (SIM)
    - Active Control
    - Multi-stage vibration suppression
  - Sunshades deployment / thermal control
  - ACS feedback data from instrument Fine Guidance Sensor
  - Case specific evaluation /development of deployable mechanisms
- Observatory can be launched to and operated from L2
- Prudent investigation of enhancing technologies may provide cost/risk reduction through subsystem upgrades

Optical Telescope Assembly

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Telescope Requirements

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Parameter	Requirement	Goal
MISSION REQUIREMENTS		
Image Quality	Diffraction Limited at 7 μm	Diffraction Limited at 3 μm
Band Pass	3 to 17 μm	0.6 to 40 μm
Collecting Area**	> 200 m^2	> 300 m^2
Aperture Diameter	> 26 m	> 50 m
Life Time	5 years	10 years
SYSTEM REQUIREMENTS		
Field of View	$\geq$ 10 $arcmin^2$	$\geq$ 10 $arcmin^2$
Telescope Mass	3600 kg	3000 kg
DERIVED REQUIREMENTS		
Operating Temperature	< 50 Kelvin	<35 Kelvin
PM Stowed Stack Height	< 7.4 meters	< 7.4 meters

** OTA temperature and gold coating allow long wavelength observations; system is limited by instruments*

*** After subtraction of central obscuration, struts, and and gaps*

OTA Wavefront Error Budget (28m Aperture Telescope)

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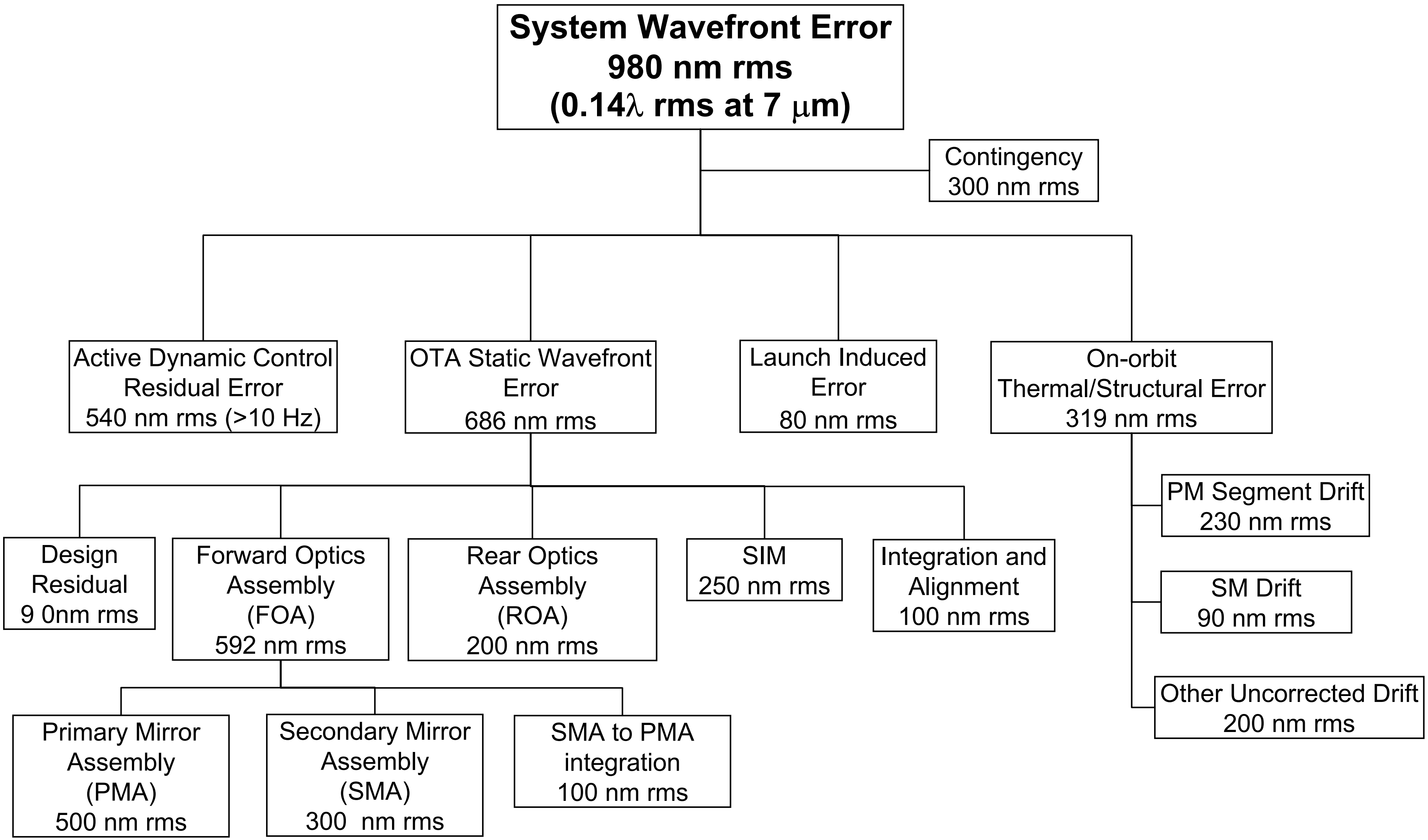

Basic Telescope Design

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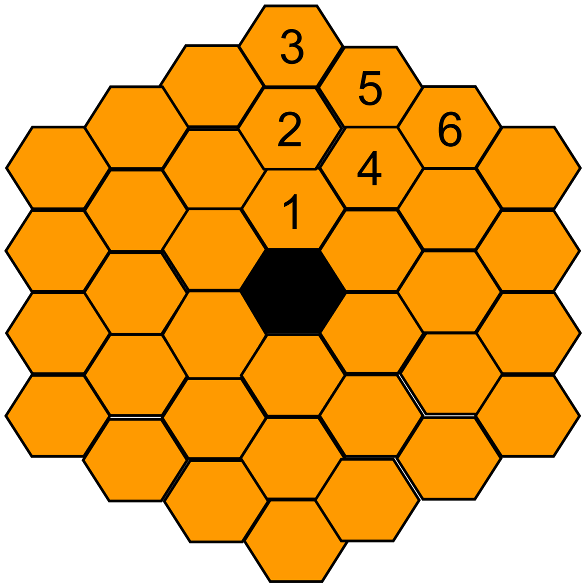

- 36 hexes on primary in three rings:
  - Manufactured via replica optics
  - Seven force actuators to control RoC, astigmatism and trefoil, plus six rigid-body actuators to control tip, tilt and piston
  - Six different hex forms
- 4-meter flat-to-flat hex dimension
- Aperture = 28 m circumscribed diameter
- F/20 OTA system provides a plate scale at the telescope focal plane of 0.367 arcsec/mm
- Three-mirror anastigmat optical form, off-axis in field, on-axis in aperture, to provide excellent stray light control and well corrected aberrations at the telescope focal plane.

Telescope Designed to Maintain Central Obscuration to Central Hex

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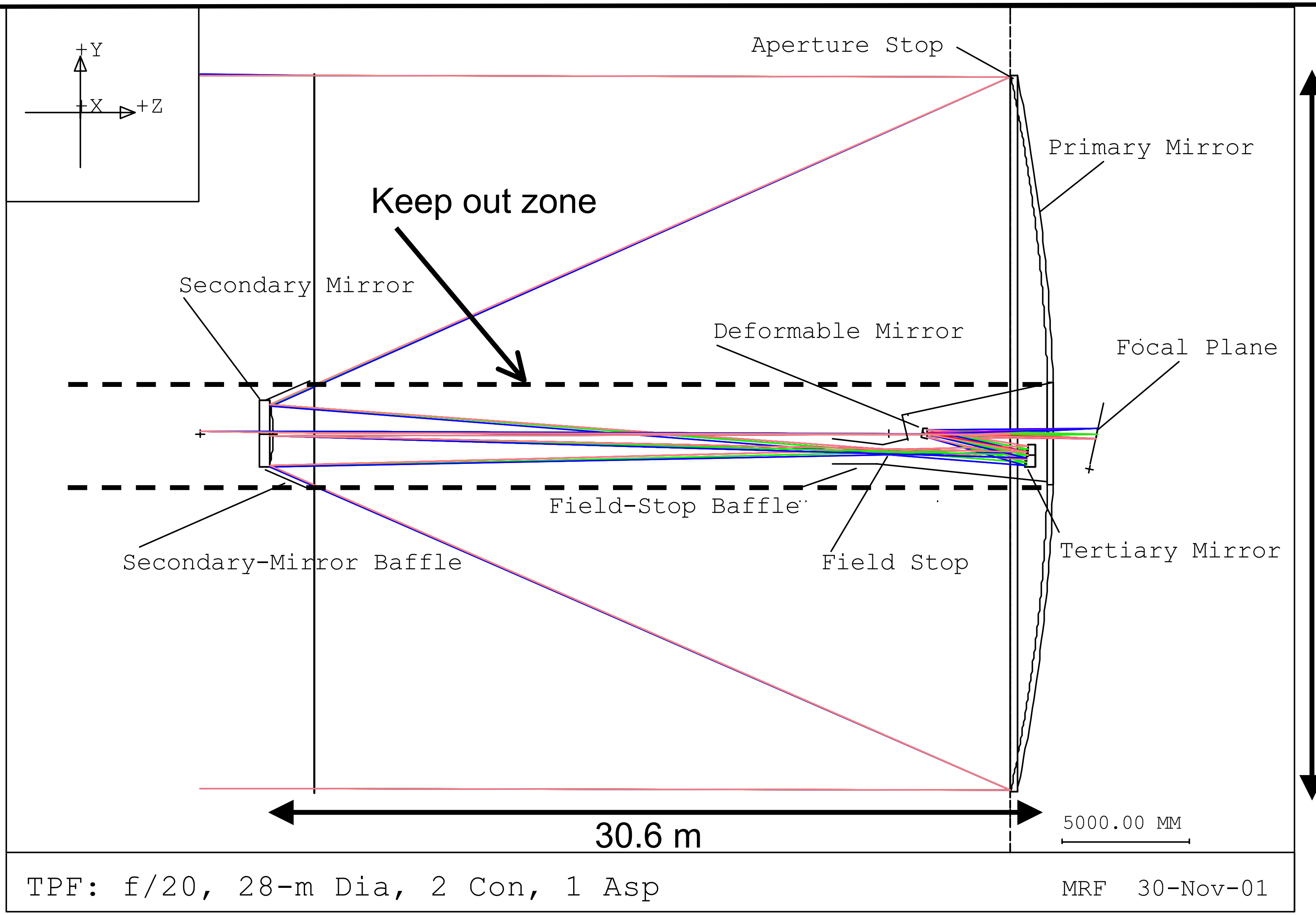
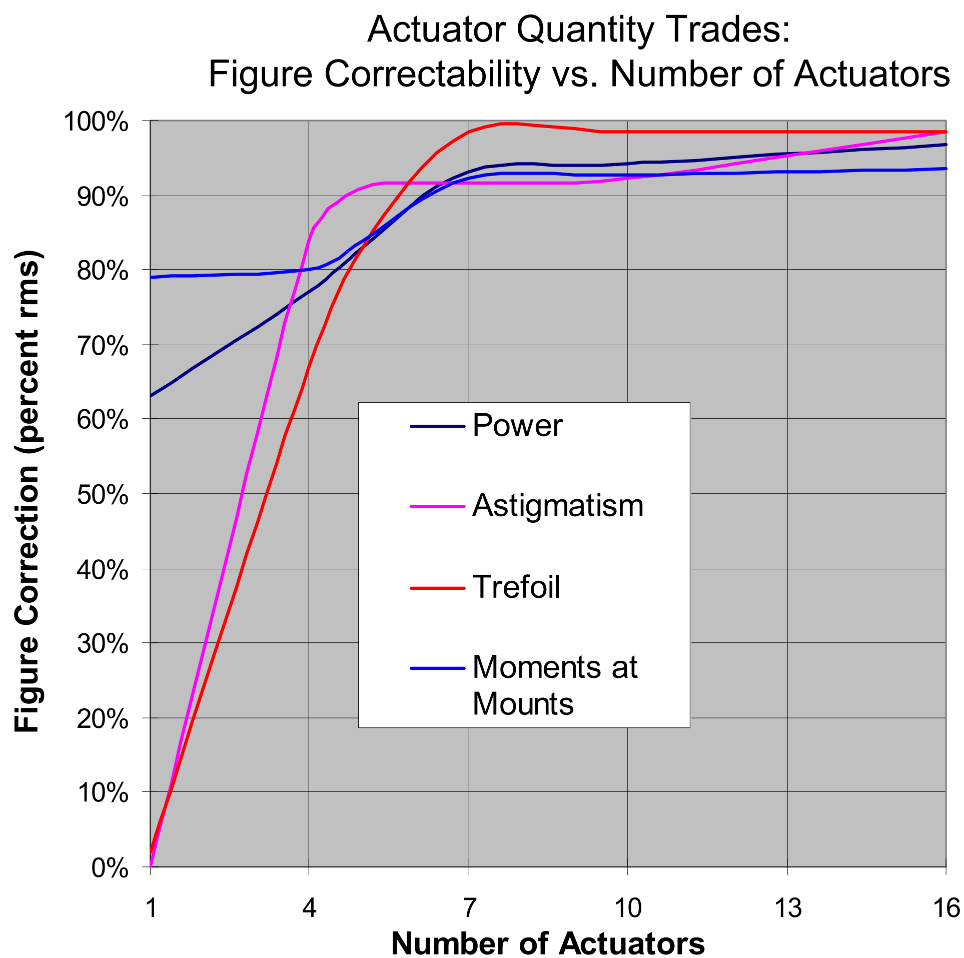


Kodak AMSD Hex-Mirror Actuator Sensitivity Study Defines TPF Needs

TRW

- Actuator density study shows seven actuators are ample for correcting low order deformations:
  - RoC, astigmatism, trefoil
  - Using Global Influence Functions to control mid-spatial frequencies from 0.5 to ~ 10 cycles/dia
  - Residual is corrected by DM with 200 actuators/dia.
- Coronagraph requires correction of spatial frequencies in the band from ~0.8 to 98 cycles/dia.



IR Coronagraphy Stringent Stray Light Requirements Met With Readily Achievable Technology

TRW

- Telescope design form selected to minimize stray light
- Surface roughness of the mirrors needs to be minimized to reduce scattered light:
  - < 10 Å RMS surface roughness from replica optics obtainable with current state of the art (for room temperature optics)
  - < 100 Å RMS surface roughness required to meet stray light requirement
  - Technology development needed for cryogenic temperatures with a goal of < 30 Å RMS surface roughness
- Mirror coatings need to have minimal phase errors and have low degradation in the space environment:
  - Selected a gold coating to minimize phase errors and handling problems
  - Gold has very good performance over wavelength range of interest
  - Gold requires no dielectric overcoating, thus has reduced scatter
  - Can operate down to 0.6 microns wavelength if desired
- General Astrophysics mission would like to image at wavelengths as short as possible:
  - OTA is diffraction limited at 7 microns (goal is DL at 3 microns).
  - Scattered light requirements also provide for reasonable images at these shorter wavelengths.

Telescope Provides a Large Field of View for Instrumentation

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- FOV has a well corrected “smile” region used for instruments with 8 to 13 μm RMS design-residual spot sizes (<0.038 X DL at 7 microns): peripheral FPA areas used for guiding
- FOV center is on-axis in X, and –0.145 deg off-axis in Y: FFOV is 0.04 deg. by 0.12 deg.
- Coronagraph: 15 arcsec square (41.19 mm) FFOV centered at (X,Y) = (0.055, -0.145) deg.

Raster pattern of spots diagrams are shown at angular positions, but enlarged to show spot size and shape.

SPOT MAGNIFICATION: 1188 Times

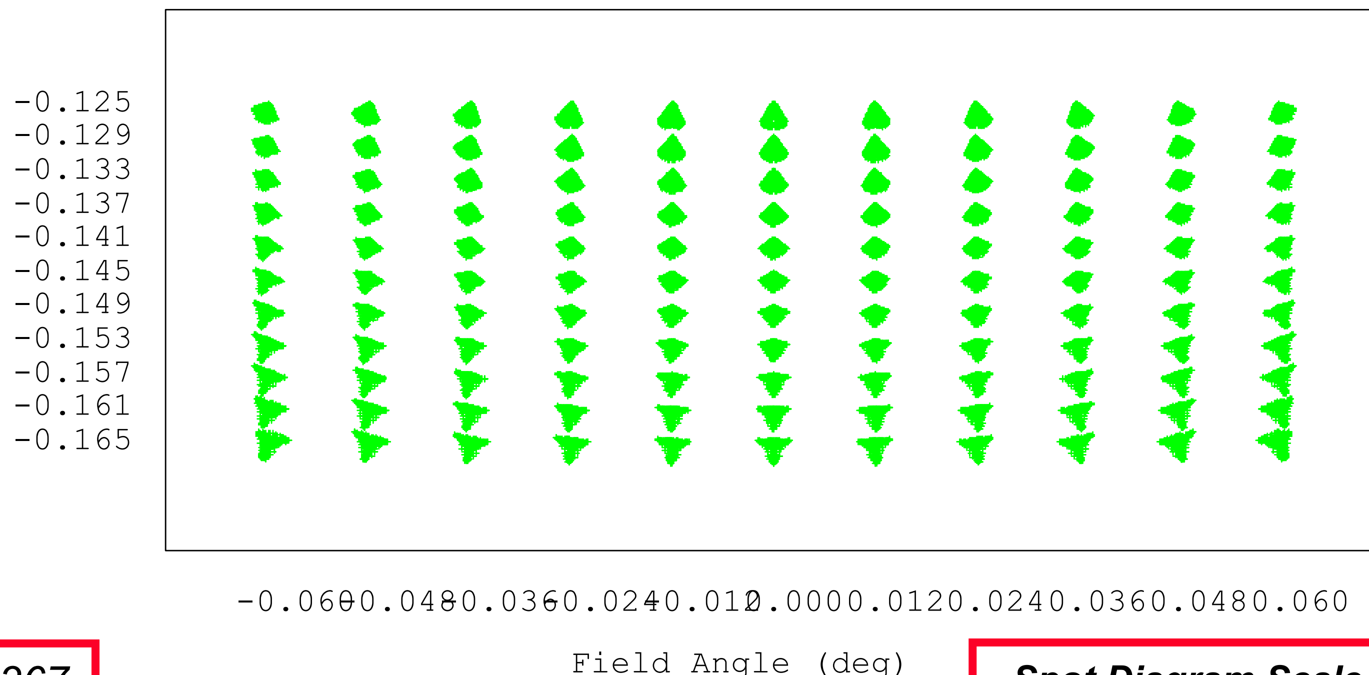

Plate Scale = 0.367 arcsec/mm

Spot Diagram Scale

0.200 mm

Optical Telescope Assembly Technology Drivers

TRW

- 4-meter segments:
  - Replica optics manufacturing (see Fabrication section)
  - Cryogenic figuring of large panels with WFE of <= 2 μm PV after active control
  - Surface roughness requirements of < 100 Å RMS with a goal of < 30 Å RMS at cryogenic temperatures
  - Areal density requirements (5 kg/m^2)
  - Mirror segment height of 20 cm
  - Demonstrate techniques for off-loading gravity to test segments figure, such as differencing between surface-up and surface-down orientations
- Deployable structures
  - Methods of deploying from stack to populated array
  - Deployment accuracies within capture range of wavefront control system

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Science Instrument Module

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Science Instrument Module Requirements

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- Fundamental goals
  – Provide the Science Data TPF will collect
  – Provide sensing for wavefront error correction and pointing correction at the Primary Mirror, the Deformable Mirror, the Secondary mirror, and the fast steering mirror(s)
- Physical requirements
  – House all optical components after the secondary mirror with sufficient structural stiffness to maintain alignment
  – Accommodate the science instruments and the guide camera
  – House electronics required for data transmission from the instrument detectors to the spacecraft data recorder
  – Provide thermal control for optics, electronics, and mechanisms as needed for operation

Potential TPF SIM Instrument Complement

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Minimum Science Instrument Module Complement

- Infrared Coronagraph (7 to 17 microns)
  - Imaging system
  - Low resolution spectroscopy included
  - Can operate as an imager for general astrophysics
- Guide Camera
  - Visible or Near IR with very high angular resolution

Included in Strawman TPF SIM Complement

- Optional Instrumentation
  - General Infrared Camera (5 to 28 microns)
    - Imaging and spectroscopy options
    - Improves General Astrophysics
  - Visible/Near IR camera/spectrometer (0.6 to 5 microns)
    - Desirable for general astrophysics
  - Longer wavelength IR camera/spectrometer (20 to 40 microns)
    - SIRTF heritage instrument

Functional Diagram of System

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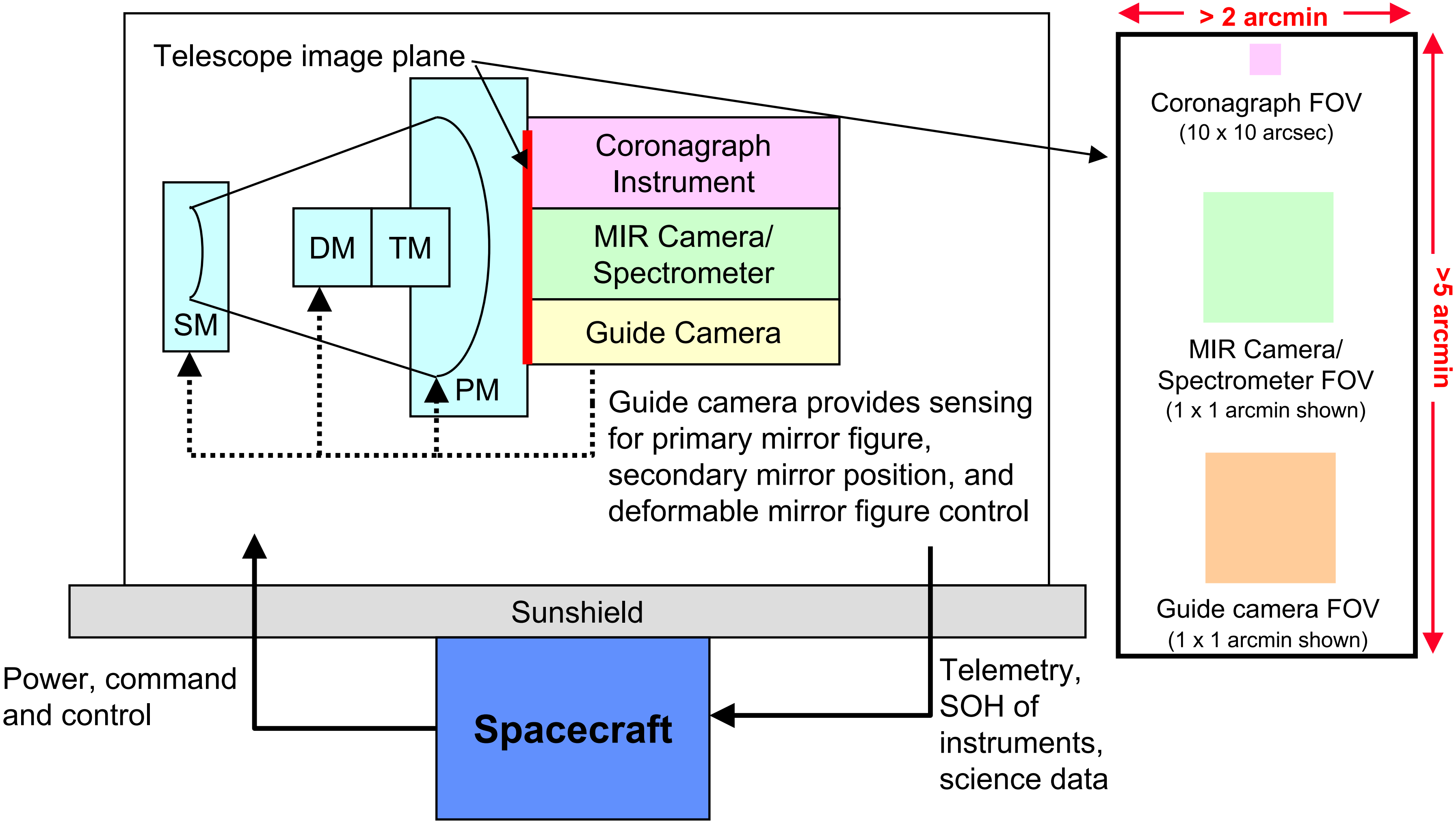

Spacecraft processor takes input from guide camera to perform WFS&C functions

Coronagraph Instrument Designed to Meet Required Angular Resolution

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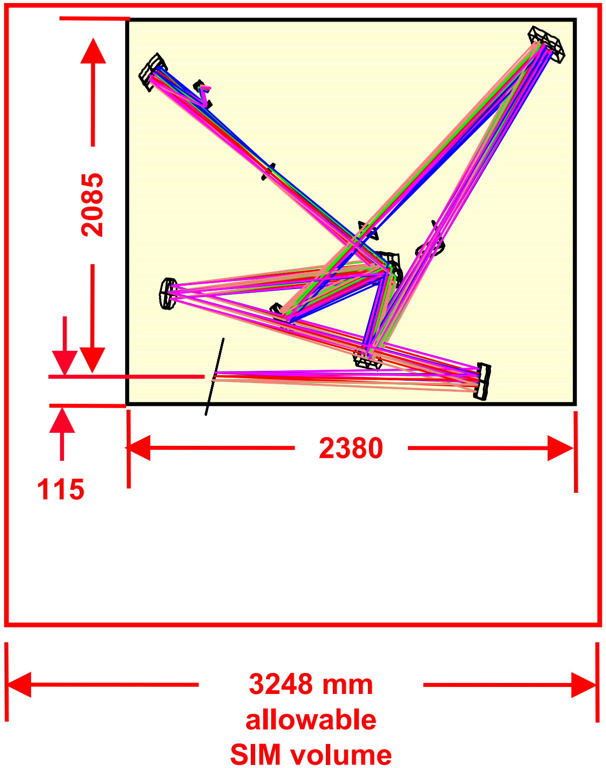
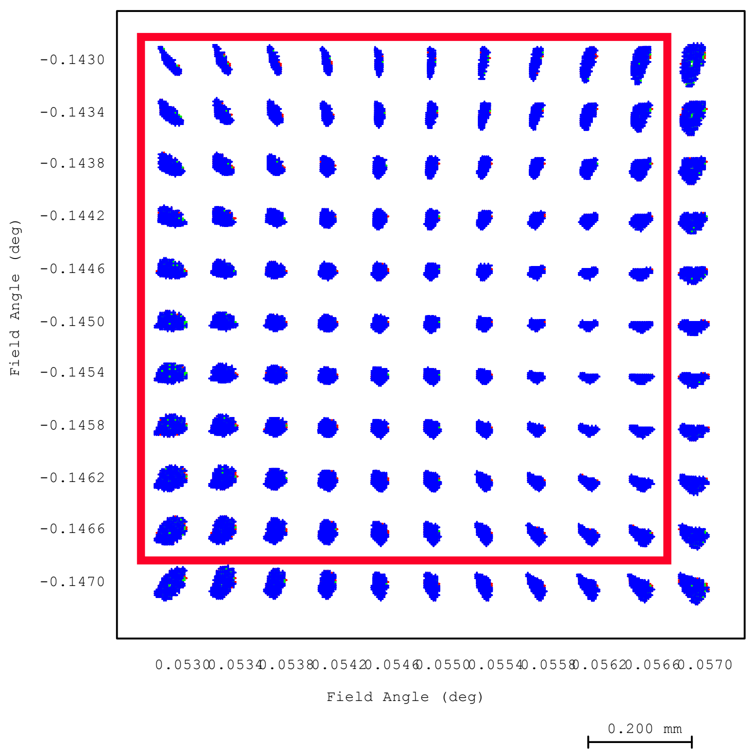
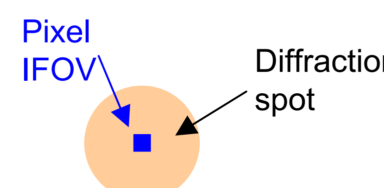


- Coronagraph optical train provides 25 mas per pixel at the detector plane on 30 μm pixels
- Volume of Instrument fits within SIM volume
- Detector images have geometrical distortions that provide diffraction limited images (due to design residuals only) at <2 μm



Coronagraph field of view (within red border is 12.8 x 12.8 arcsec as used) with image spots shown enlarged for clarity (to scale bar)

Pixel IFOV and FWHM of diffraction spot at 10 μm shown on same scale as spots below



The TPF SIM Provides Ample Room for Multiple Instruments

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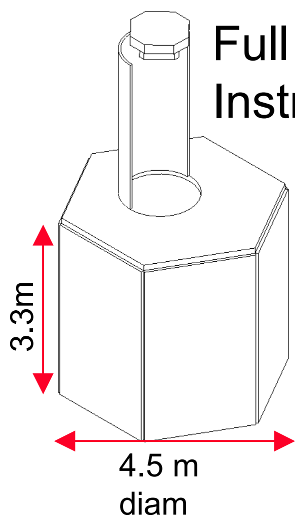
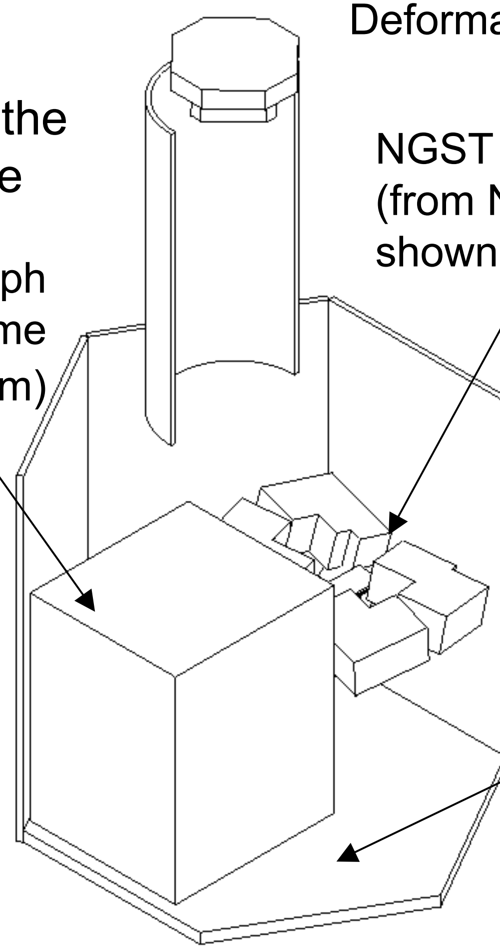


Full Science Instrument Module

Radiators for electronics/ cryocooler waste heat can be mounted on outer surfaces

Cut away view of the Instrument Module



Deformable Mirror

NGST NIR Camera (from NASA/GSFC) shown for comparison

Coronagraph Instrument Volume (2.1 x 1.6 x 2.4 m)

Electronics and cables to communicate with spacecraft can fit in this area

Remaining volume for Guide Camera and potential additional science instruments

The Coronagraph Supplies Internal High Accuracy Guiding

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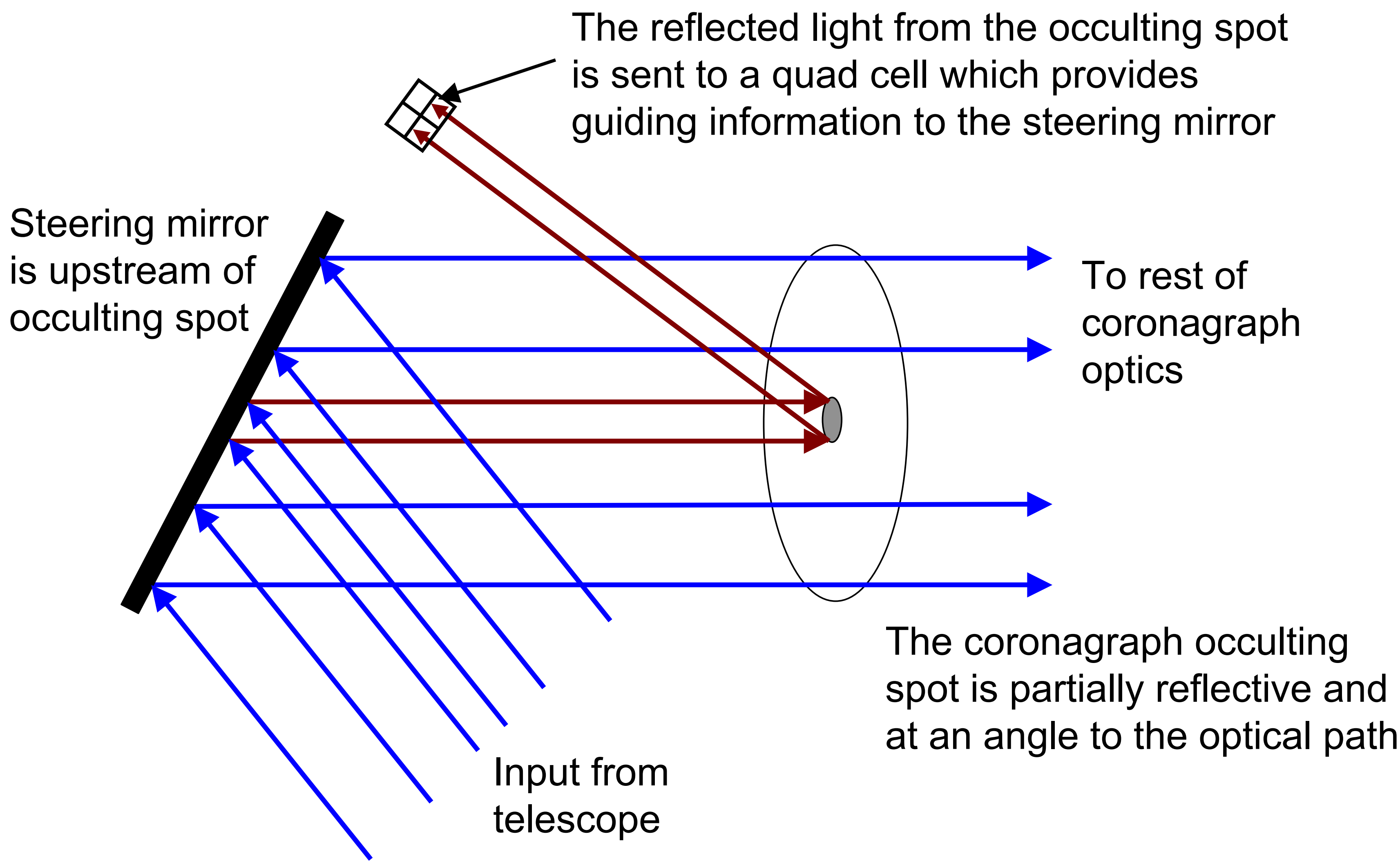

Instrument Characteristics

	λ (μm)	IFOV (mas)	FPA size (pixels^2)	FOV (as^2)	Comments
Guide Camera (Guide *and* Wide Field / Acquisition modes)	3-5	10 *and* 60	1024	10 *and* 60	HgCdTe likely. Run fast enough to drive the steering mirror for guiding. Baseline a magnification for Guiding Mode. Could be separate units for Guide Mode and Wide Field Acquisition Mode. Based on NGST science instrument and guider.
IR Coronagraph	7-17 (5-28)	20	512	10	Base on Eclipse testbed heritage. Filter wheel and spot wheel to optimize detection based on stellar type & expected separation; dispersive gratings for low resolution spectra for characterization
IR Imaging Camera / Spectrometer	5-28	60 or 30	1024 or 2048	60 to 120	Largest available Si:As detector. Dual filter wheels, CVF, grisms, spectrometer pickoff are all options. Base on NGST MIR camera, and SIRTF spectrometers.
Optional: Vis/NIR Imager	0.5-5	15	4096 (NGST based)	60	InSb or HgCdTe detector as used for NGST. IFOV driven by figure errors of primary mirror. Short wavelength cutoff driven by mirror coating.

Technology Needs for TPF SIM

TRW

- IR Detector Technology
- Si:As detector developments
  - ✯ Formats >512 x 512
  - – Dark current < 30 e^-/second
  - – Readout noise < 100 e^-
- 0.5 - 5 μm in single detector
  - – AR coatings
  - – Material performance
- High speed, large format detector for guide camera
- Cryo-cooler development
  - – Long life
  - – High efficiency, low power
  - – 6 K coldhead
  - – Cryogenic compressor

- Optics Technology
- ✯ Large IR filters (5-28 μm)
- Packaging of spectrometer with imager
- Broadband transmissive substrates
- Apodization technology for Lyot stop and occulting spot
- Magnification techniques for guide camera

Other Technology

- Low power, cryogenic electronics for FPA signal conditioning
- Low power drivers for filter wheels and other mechanisms
- ✯ Reliable cryogenic mechanisms

NGST Development programs in **RED**

✯ Denotes Enabling Technologies

Science Performance Modeling

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UCLA Astronomy

TPF Terrestrial Planet Finder

Performance Model Includes Many Details as Inputs

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Star temperature

Distance to Star

Planet temperature

Planet-Star separation

Endo-zody (DIRBE model)

Exo-zody scaled from endo-zody, up to 10x solar value

Aperture collecting area
- Aperture size/# hexes
- Physical obscurations
- Lyot masking

Coating reflectivity

Occulting spot diameter and apodization

Mirror thermal emission

Detector parameters

Filter and transmissive element transmission

Performance Model

Uncompensated jitter

Mirror segment misalignment

Integration time

Spectral resolution

Maximum single integration time (limited by cosmic ray flux)

SNR

Assumptions in Performance Model Allow Fast Scaling Computations

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Occulting spot modeled as a modified Gaussian (per J. Trauger) with 10^{-8} transmission in the center and 10^{-4} transmission at the specified radius

Airy diffraction pattern modeled for circular aperture of maximum dimension of hexagonal mirror

Modified airy pattern due to apodized Lyot mask included as an option (the "Hanning taper")

Lyot mask effects modeled as a constant 10^{-2} suppression of diffraction energy

Signal strength scaled by encircled energy and total flux calculations

Jitter and panel misalignments modeled as a broadening of the airy pattern

Planet and Star modeled as blackbodies

Reflected light component assumes Lambertian scattering from planet and that planet disk is only half illuminated

Exo-zody is 2 times the endo-zody flux for the same view angle multiplied by a factor of 0.1 to 10

Single pixel SNR calculated (multi-pixel SNR better)

Solar system at 10 pc is used as a benchmark

Phi 2 Pav used as "typical" system from Simon & Vogt Golden Oldies target list

Model Used to Evaluate Instrument Technology Needs

TRW

- Detector improvements can reduce integration time
  - Reducing the read noise to 25 e^- as achieved on SIRTF instead of 100 e^- results in ~4% reduction in characterization mission time
  - Increasing the QE (modeled as 41% at 10 μm) of the detector is a larger effect
    - 45% QE reduces overall integration time by 10%
    - 50% QE reduces integration time by 20%
    - Improvements limited by the physical properties of the material
- System transmission improvement has similar effects to improving detector QE
  - Unlikely to improve reflectivity of gold coated mirrors significantly
  - Can improve filter transmission
  - Can improve substrate transmission for the occulting spot
  - Improvement directly related to the improvement in the overall transmission of the optical system

These results indicate that the telescope system operates in or near the background limited performance regime for both the planet detection and characterization missions

Model Used to Compare Visible Light to Mid-IR for Detection Mission

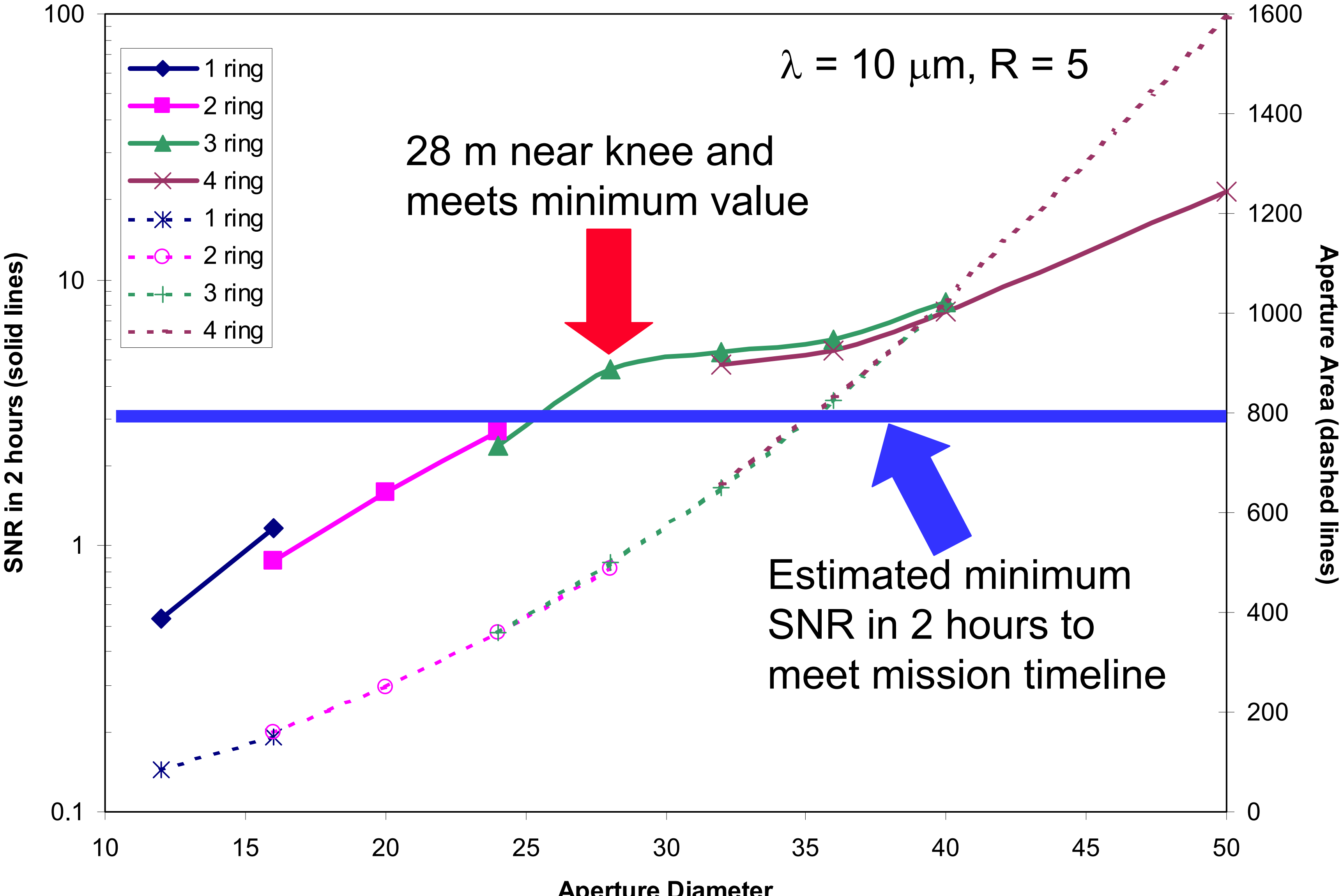
TRW

- Visible inner ring, λ=0.6 μm
  - D = 12 m
  - Collecting area ~ 47 m^2
  - InSb detector (NGST heritage)
  - Assume all silver coatings
- Infrared, 36 hexes, λ=10 μm
  - D = 28 m
  - Collecting area ~ 257 m^2
  - Si:As detector (SIRTF/ NGST heritage)
  - Mirror temperature = 30 to 50K
  - Detector cold shield temperature = 10K

- Comparisons done for single pixel SNR
  - SNR increases if sum over the PSF
  - If spot profile is not divided out, location of planet will be in error if close to the spot 1/2 power point
- For solar system at 10 pc using a hard-edged Lyot stop:
  - IR better for inner planets
  - Visible has better SNR for outer gas giants due to large surface area
  - Visible becomes equivalent with IR if apodized Lyot mask is used
- For other systems:
  - Visible SNR is better than the IR for planets <80 mas from the star
  - IR SNR can be improved by optimizing the spot size and the observing wavelength $\Rightarrow$ need multiple spots and filters in coronagraph instrument

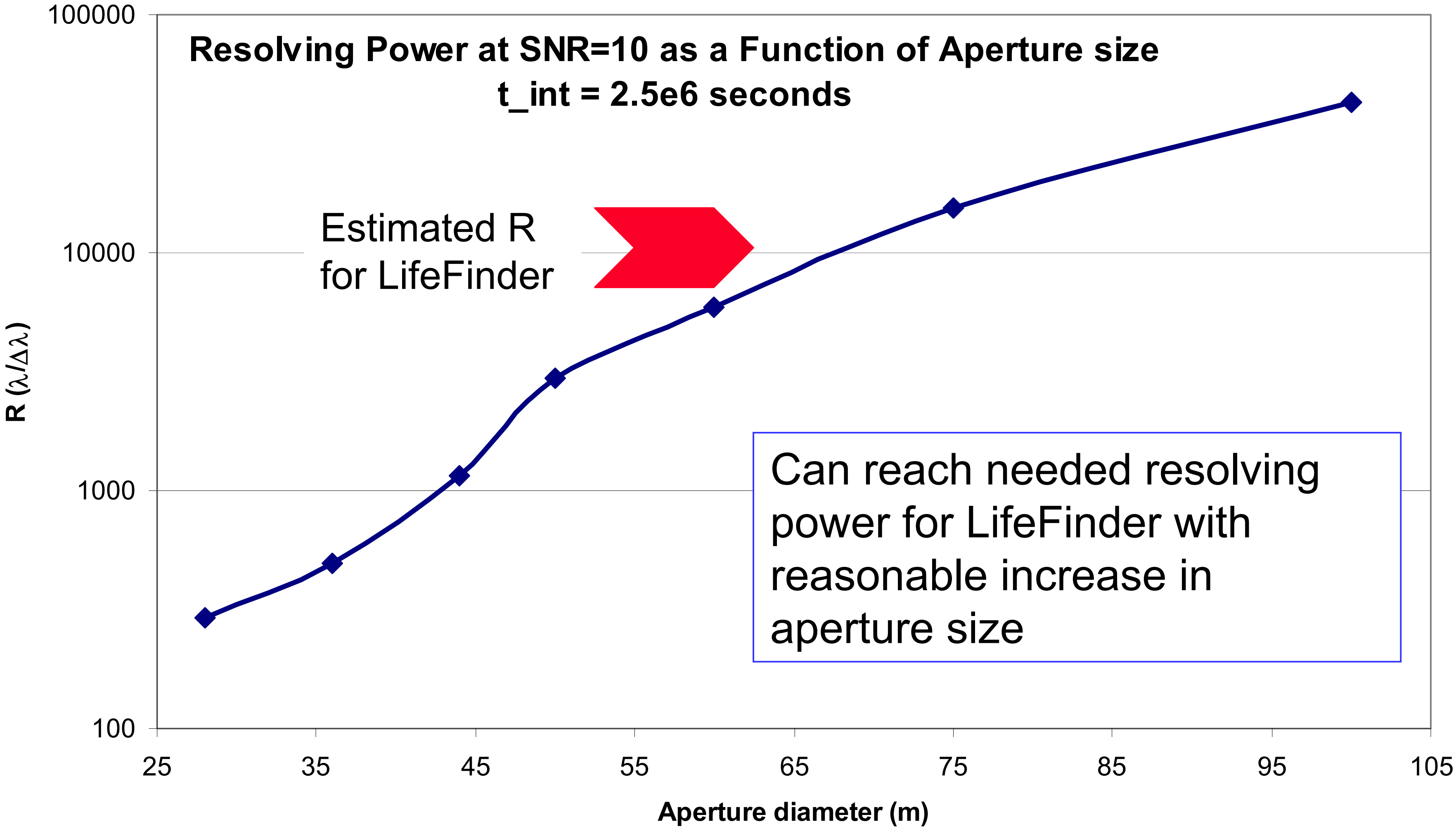
Model Used to Determine Minimum Size of the Aperture for this Mission

TRW



Model Used to Show Scalability of Approach to Life Finder Mission

TRW



Results for Planet Detection Mission

TRW

Parameter	Value	Units
Primary Mirror Diameter	28	m
Number of Hexes	36	
Wavelength	10	microns
Integration time	2	hours
Pixels in FOV	512	
IFOV (per pixel)	0.0250	arcseconds
Distance of Star	24.2	parsecs
Overall optics thruput	0.6150	Read from optics
Spectral Resolution	5	$\lambda/\Delta\lambda$
Maximum single t_exp	901	seconds (NGST)
Pixel size	30	microns
Instrument temperature	10	K
Optics Temperature	50	K
Exo-zody (factor * Earth)	1	0.1 - 10x
Detector Parameters (from Detector worksheet)		
Dark current 1	30	electrons/sec
Read noise 1	100	electrons
QE 1	0.407	Si:As
Optics emissivity 1	0.1	
Occulting Spot Parameters		
Spot FWHM	80	mas
Attenuation	8	10^x
Lyot stop atten	1.00E-02	on diffraction
Apodized Lyot?	0	1=yes, 0=no
System Parameters		
Mirror panel vibration alloc.	3	mas
LOS error allocation	3	mas

Case	Time to SNR = 5 for R=5, λ=10 μm
Earth @ 10 pc	2.4 hours
Phi2Pav @ 24.2 pc	71.2
DYEri @ 5 pc	0.4
HIP 48113 @ 18.4 pc	12
71 Ori @ 21.1 pc	73.5
HIP 92549 @ 26.1 pc	783 hours, or 101 hrs @ 8 μm, & 17.6 hrs @ 8 μm w/ 60 mas occulting spot

Multiple occulting spots and filters required for detection mission

"Average" integration time per target is estimated to be ~20 hours

Results for Planet Characterization Mission

TRW

Parameter	Value	Units
Primary Mirror Diameter	28	m
Number of Hexes	36	
Wavelength	10	microns
Integration time	10	hours
Pixels in FOV	512	
IFOV (per pixel)	0.0250	arcseconds
Distance of Star	24.2	parsecs
Overall optics thruput	0.6150	Read from optics
Spectral Resolution	20	$\lambda/\Delta\lambda$
Maximum single t_exp	901	seconds (NGST)
Pixel size	30	microns
Instrument temperature	10	K
Optics Temperature	50	K
Exo-zody (factor * Earth)	1	0.1 - 10x
Detector Parameters (from Detector worksheet)		
Dark current 1	30	electrons/sec
Read noise 1	100	electrons
QE 1	0.407	Si:As
Optics emissivity 1	0.1	
Occulting Spot Parameters		
Spot FWHM	80	mas
Attenuation	8	10^x
Lyot stop atten	1.00E-02	on diffraction
Apodized Lyot?	0	1=yes, 0=no
System Parameters		
Mirror panel vibration alloc.	3	mas
LOS error allocation	3	mas

Case	SNR=10 @ 10μm for R=20	SNR=25 @ 10μm for R=20
Earth @ 10 pc	42.3 hours	265 hours
Phi2Pav	1339	N/A
DYEri	6.5	40.3
HIP 48113	234	1462
71 Ori	1348	N/A
HIP 92549	13340 (N/A)	N/A
"Average"	~340	~670

- Number of planet photons received is the principle driver of integration time
- Distance to the star is driver
  - ⇨ Planet modeled as 270 K, R = 6200 km
- Detailed investigation limited to close systems (D<20 pc) due to lack of flux

Performance Model Shows 28 m IR Coronagraph Approach Is Feasible

TRW

- Mission can be accomplished in 2.5 years allocated time
- Detection mission will need to be tailored to specific stellar system
  - Close in targets will need smaller occulting spot operating at shorter wavelengths
  - For wider separations, get more photon flux at longer wavelengths so shorter integration times are obtained
  - Revisit time will be tailored to expected orbital period
- Characterization mission is challenging
  - Technical challenges to collect spectra simultaneously
  - Distant targets not feasible in limited mission time
  - Improvement would be obtained with better transmission of the optical train or improvements in detector QE
  - Time chosen for the characterization observation will need to be selected based on the planet's orbital characteristics such that planet is near maximum separation

A Large Aperture IR Telescope Can Meet Many Other Science Needs:

General Astrophysics with an IR Coronagraph

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What Astronomers Want

TRW

- Large collecting area
- Good angular resolution
- Good spectral resolution
- Large field of view
- Wide wavelength range

An instrument that provides all of these can also detect and characterize terrestrial planets, but can we afford it?

Other Astrophysical Capability

The front end of the large aperture IR Coronagraph is the N^2GST

It has great power for the kinds of projects astronomers do now

General Astrophysics Capabilities

TRW

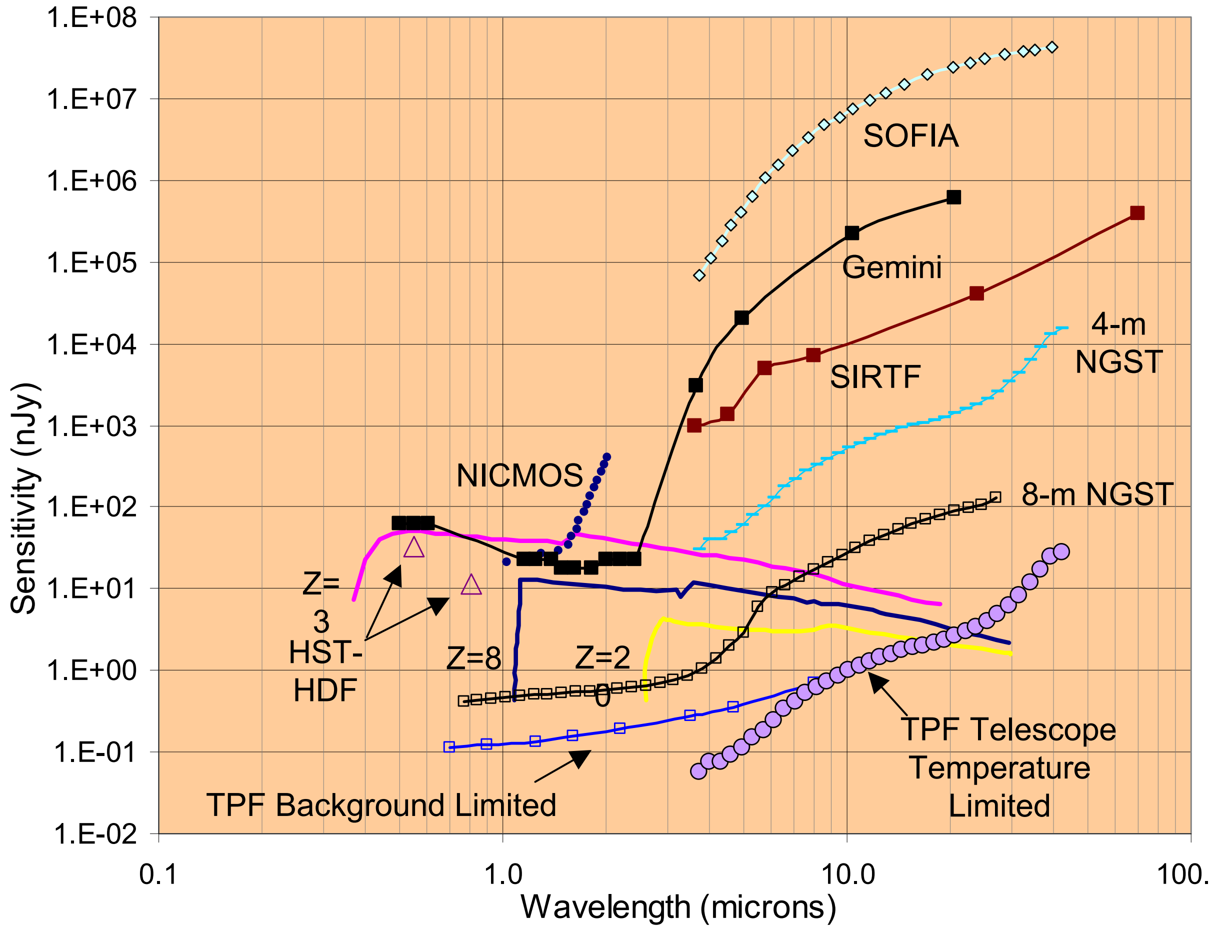
Assume D = 28 m, Jitter+aberrations FWHM = 0.01”, 6 hr integration, 5σ point source sensitivities

Wavelength	Flux limit in t_{int} = 6 hours	Angular Resolution
0.7 μm	0.12 nJy	12 mas
0.9	0.13	13
1.25	0.14	15
1.6	0.16	18
2.2	0.20	22
3.5	0.29	33
4.7	0.37	43
8.0	0.74	73
10.0	1.04	90

Sensitivity of Infrared Observatories

TRW

- TPF point source sensitivity compared with other IR Observatories for
  - Integration time = 10,000 sec
  - Resolution ($\lambda/\Delta\lambda$) = 5
  - Signal to Noise = 5σ
- The 4-m and 8-m NGST and the 28-m TPF telescopes are assumed to have optics with an equilibrium temperature of 35K and emissivity of 0.05
- The zodiacal light background limits NGST and TPF sensitivity for $\lambda<15\mu m$



Particular Astrophysics Goals

TRW

- Distance scale
  - Cepheids
  - Surface brightness fluctuations
- Dark energy – supernovae
- First objects in the universe
- Disks and outflows around protostars
  - Imaging
  - Dynamics
- Disks and jets in active galactic nuclei
  - Imaging
  - Dynamics
- Spectroscopy of faint SIRTF and NGST discoveries
- Spectroscopy of faint galaxies

Distance Scale

- Cepheids, 5σ in 6 hrs for 25-day period
  - 750 Mpc in J band, z=0.16
  - 475 Mpc in K band, z=0.1
- IR Surface Brightness Fluctuations
  - 10x better angular resolution than HST
  - Reach out to Gigaparsecs

Dark Energy

TRW

- Median Type Ia Supernova at z=3 for H_o=65, Ω_m = 0.3 flat cosmology:
  - V-band redshifted into K-band, flux is 74 nJy
  - Imaging SNR of 370:1 in 6 hours
  - Follow light curve for many months
  - Spectroscopy is feasible

First Objects

TRW

- Super starclusters have been seen in NGC 5253 with $L = 10^9\ L_\odot$
- At z=19 for H_o=65, Ω_m = 0.3 flat cosmology:
  - 110 nm redshifted into K-band, flux is 0.3 nJy
  - Imaging SNR of 10:1 in 6 hours
  - Narrowband photometry is feasible

Disks Around Protostars

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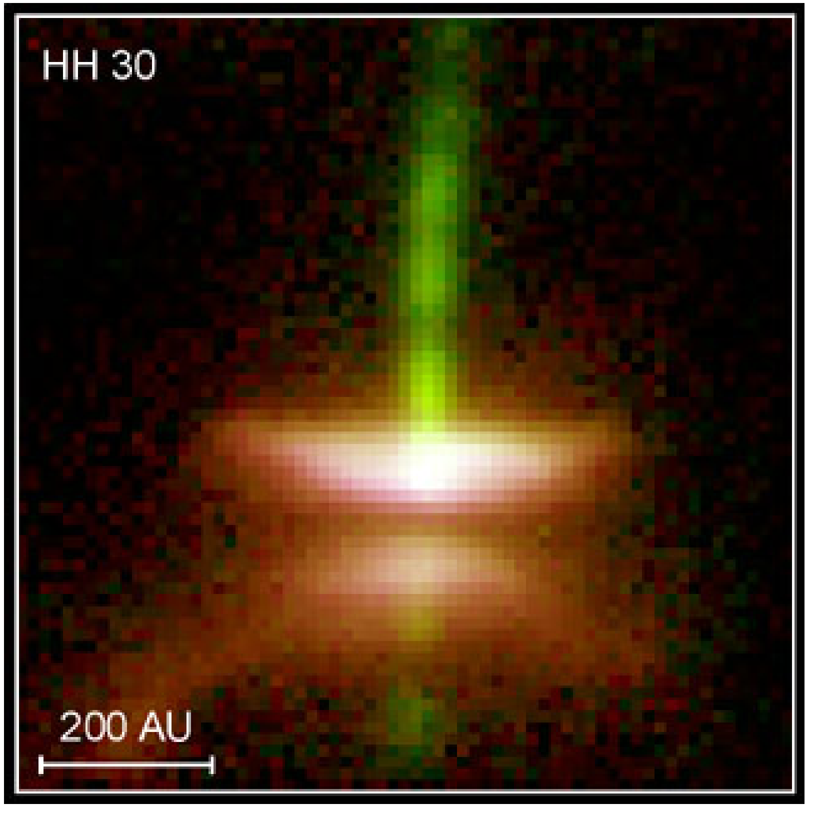
- Surface brightness will be high
- Angular size: 10's of AU at 100 pc = 0.1 to 1 arcsec
- Radial velocities of 10's of km/sec
- The large aperture IR Coronagraph will provide 10 times better angular resolution than this WFPC-2 image



Planetary Debris Disks

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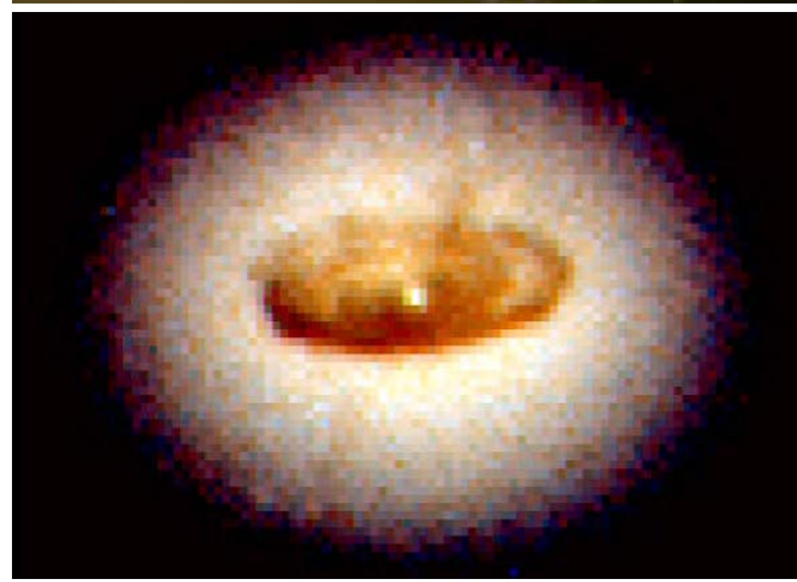
- The large aperture IR Coronagraph will be sensitive to low surface brightness structures
- This makes detection and imaging of planetary debris disks such as the Vega or β Pic disks quite simple
- Can study stars 10x more distant or provide details on 10x finer scale than current data

Active Galactic Nuclei

TRW

- 10’s to 10,000’s of AU at 10’s to 1000 Mpc giving 10 nas to 1 arcsec
- 500 to 10,000 km/sec radial velocities
- Surface brightness in IR?



Spectroscopy of Faint Galaxies

TRW

- NGST will work to z=5 or more
- For higher redshifts, need:
  - Thermal IR
  - $\lambda / \Delta\lambda = 1000$
- The large aperture IR Coronagraph will be excellent for studying these low surface brightness objects

Astrometry

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- Central 1 arcsec of MW
  - Proper Motions of 5 mas/yr
  - Radial velocities of 100's of km/sec
- "Visual" observations of spectroscopic binaries for distance scale
- Absolute parallaxes?