Fabrication, Assembly, and Test

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PM Segment Production

Mandrel Fabrication → Mandrel Production → Layup Surfaces → Cryogenic test → Coat

- **Mandrel Fabrication**: Convex mandrels similar to FIRST mirror produced by COI; convex metrology using Bauer's SBIRS-funded metrology
- **Mandrel Production**: One mandrel for each of six different prescriptions; each mandrel is comprised of six isosceles triangles individually generated and bonded together
- **Layup Surfaces**: Using a combination of FIRST mirror layup design for stiffness and CMA's surface treatment for low surface roughness
- **Cryogenic test**: Re-use NGST test facility
- **Coat**: Requires new 4.5-m capability located at cryogenic test facility

- Driving Manufacturing technology developments
  - Moderate improvement in mold surface figure and surface roughness
  - Extrapolation to 4.5 meters at low areal density while maintaining controlled fiber angles and resin content
  - Resin selection to achieve low CTE, vacuum and space qualification, and very smooth surface
  - Implementing dimple-free actuators on back for figure control
  - Production of 36 segments (500 m^2) in 45 months

TPF Assembly and Test Driving Issues

TRW

- Verification methodology is a significant potential cost driver
  - TPF's large aperture and low stiffness precludes high fidelity optical verification on the ground
  - Sunshield's 35 m x 50 m size makes verification a challenge
    - Extrapolating NGST and other TRW deployment verification techniques reduces technology challenge
    - Thermal verification will be extrapolated from NGST
  - Result is a verification process that relies on component verification and modeling to extrapolate to on-orbit performance
    - Significant reliance on model correlation and model validation with performance predictions from correlated models providing final verification
    - Great Observatories program used this to some extent for thermal performance sensitivities
    - Other programs have used this process successfully
    - NGST will make greater use of this, and validate the process for TPF
- Contamination
  - Similar to NGST, the PM and SM are scattering sources for thermal emitters
  - Experience base from Chandra ($5x10^{-5}$ FAC) and NGST should provide protocols and cleaning necessary for large aperture surfaces

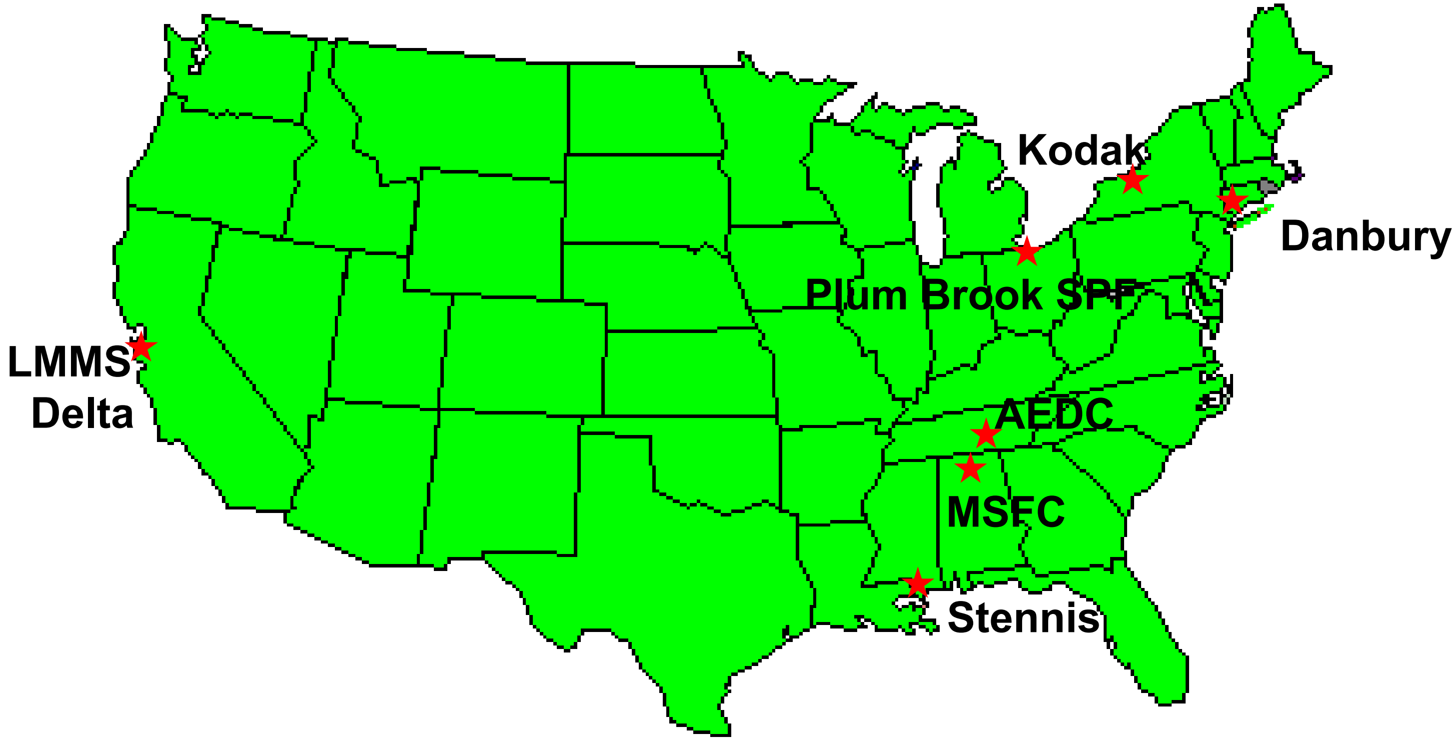
TPF Assembly and Test Facilities

TRW

- Facilities
  - Cryo-figuring of segments requires a 5-meter cryogenic chamber
  - 35-m RoC => chamber must be long and/or have a large window
  - Sunshield requires 70 m x 50 m x 35 m high bay
  - SIM requires cryogenic verification
    - GSFC's SES chamber upgrade for NGST may suffice
- Deployment accuracy verification through large-scale photogrammetry
- Telescope Integration requires reasonably large high bay
  - Horizontal integration of the telescope
  - 45 m long x 35 m wide x 35 m tall
- Observatory integration will occur in same location as telescope
- Launch processes use standard EELV facilities

TPF Mirror Segment Testing Requires Large Cryogenic Chamber

TRW

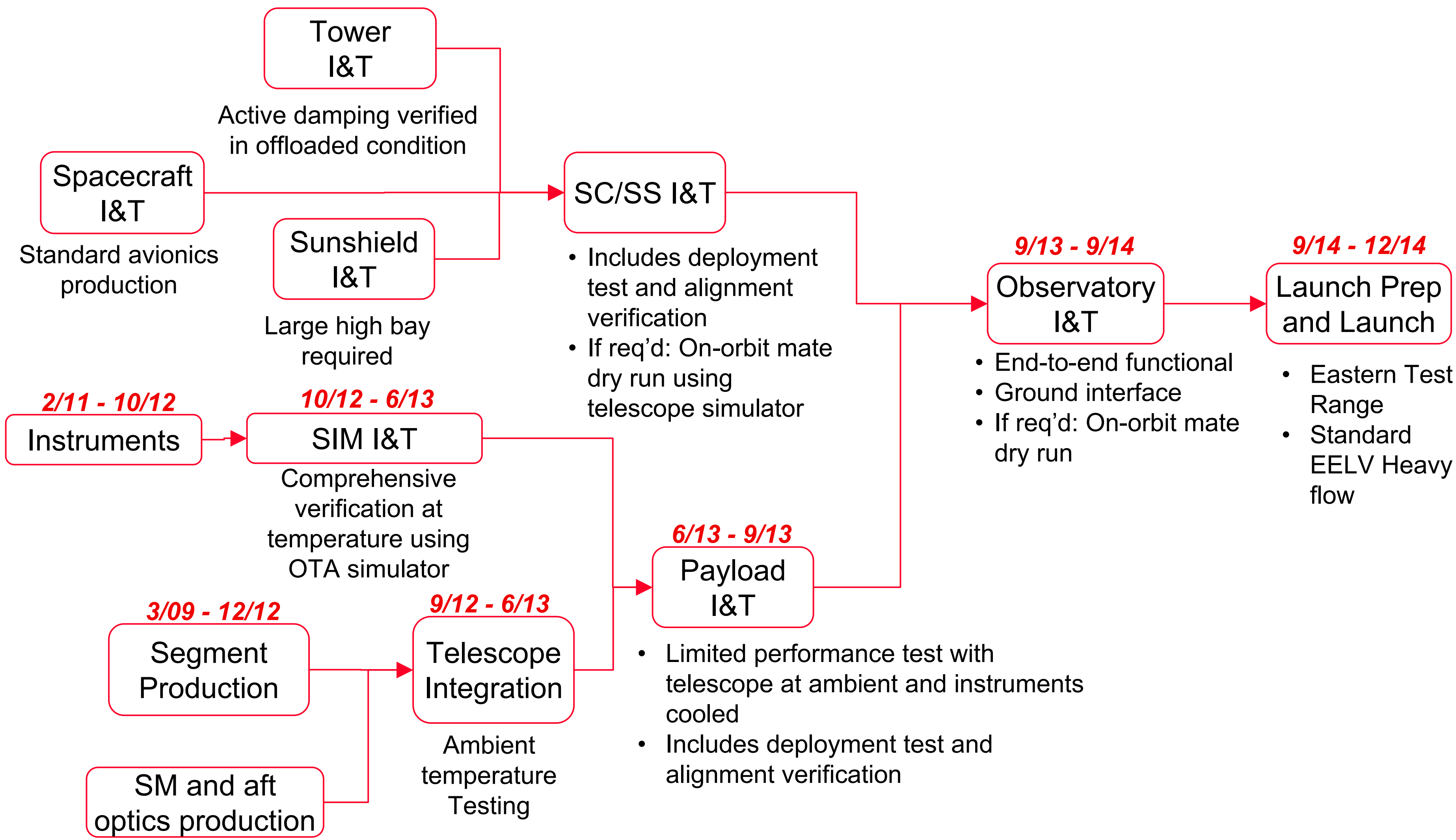


	MSFC*	SPF*	Delta*	AEDC*	Stennis	Danbury*	Kodak*
Access	Tennessee River and air	Great Lakes and air	SF Bay and air	de-commissioned runway	Gulf access and air	Road travel required	Great Lakes and air
Comment	Shroud requires significant modification	Helium refrigeration	Helium refrigeration; horizontal	Helium refrigeration	Does not currently exist - SBL plan	Chamber mods required; Helium refrigeration	Chamber mods required; Helium refrigeration

* potential NGST test facility

TPF Integration and Test Flow

TRW



Launch and Commissioning

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Launch and Commissioning Trades Need to Consider Many Factors

TRW

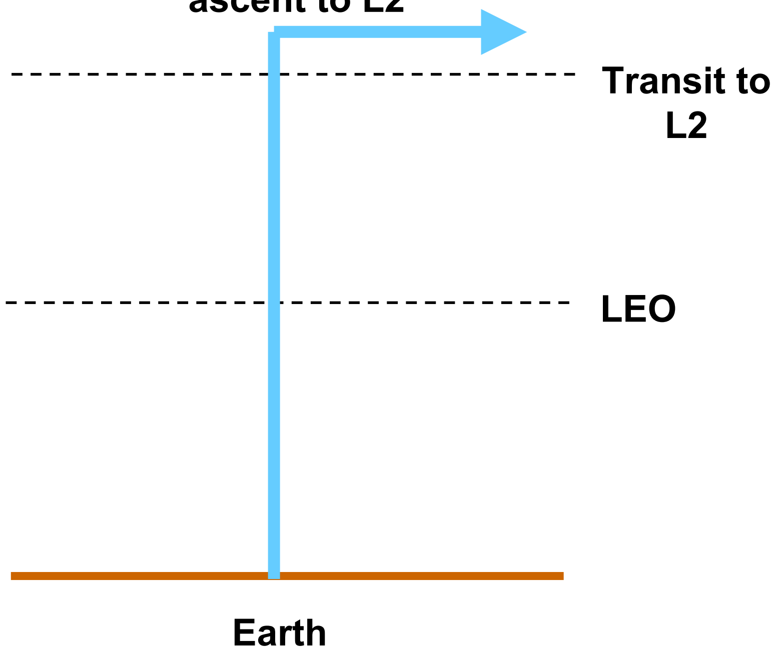
- Place of order 10,000 kg (dry mass) system into L2
  - Single vs. multiple launches
- Support Observatory deployment and check out of telescope performance
  - Can Observatory benefit from astronaut assistance in LEO?
- Avoid excessive forces (i.e., high g's at burn out of injection stage) on deployed flight system
  - Drives selection of thrust for injection stage
  - Trade whether deployment occurs before or after major Δv maneuvers
- Avoid expensive new LV developments
- Verify performance of Wavefront Sensing and Control (WFS&C) systems and science instruments

Ability to Put TPF at L2 in One Launch Depends on LV Capabilities

TRW

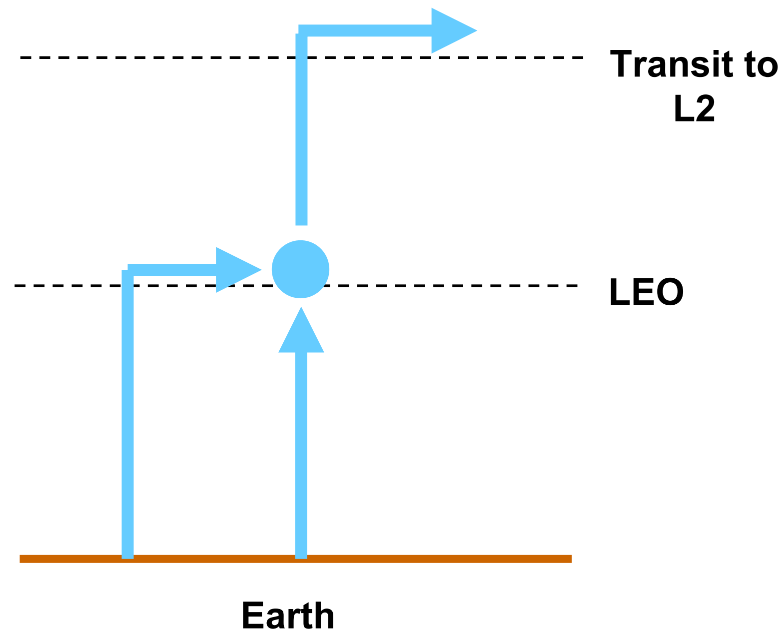
Baselined

Single-launch direct ascent to L2



Existing LVs may have sufficient capability

Multiple-launch with rendezvous and docking in LEO then inject into trans L2 orbit

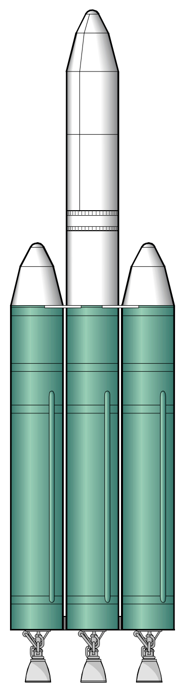


Can use existing LVs; allows LEO checkout and astronaut assistance

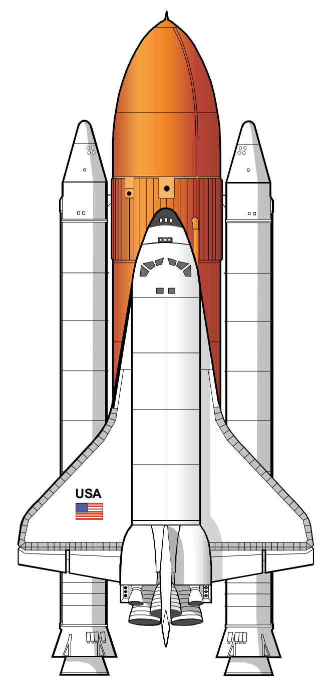
TPF Will Require the Most Capable LVs Available

TRW

- EELV-Heavies
- 5-m fairings available
- Up to 25,000 kg to 400 km LEO
- Up to 11,000 kg to L2 direct
- No special restrictions on P/L

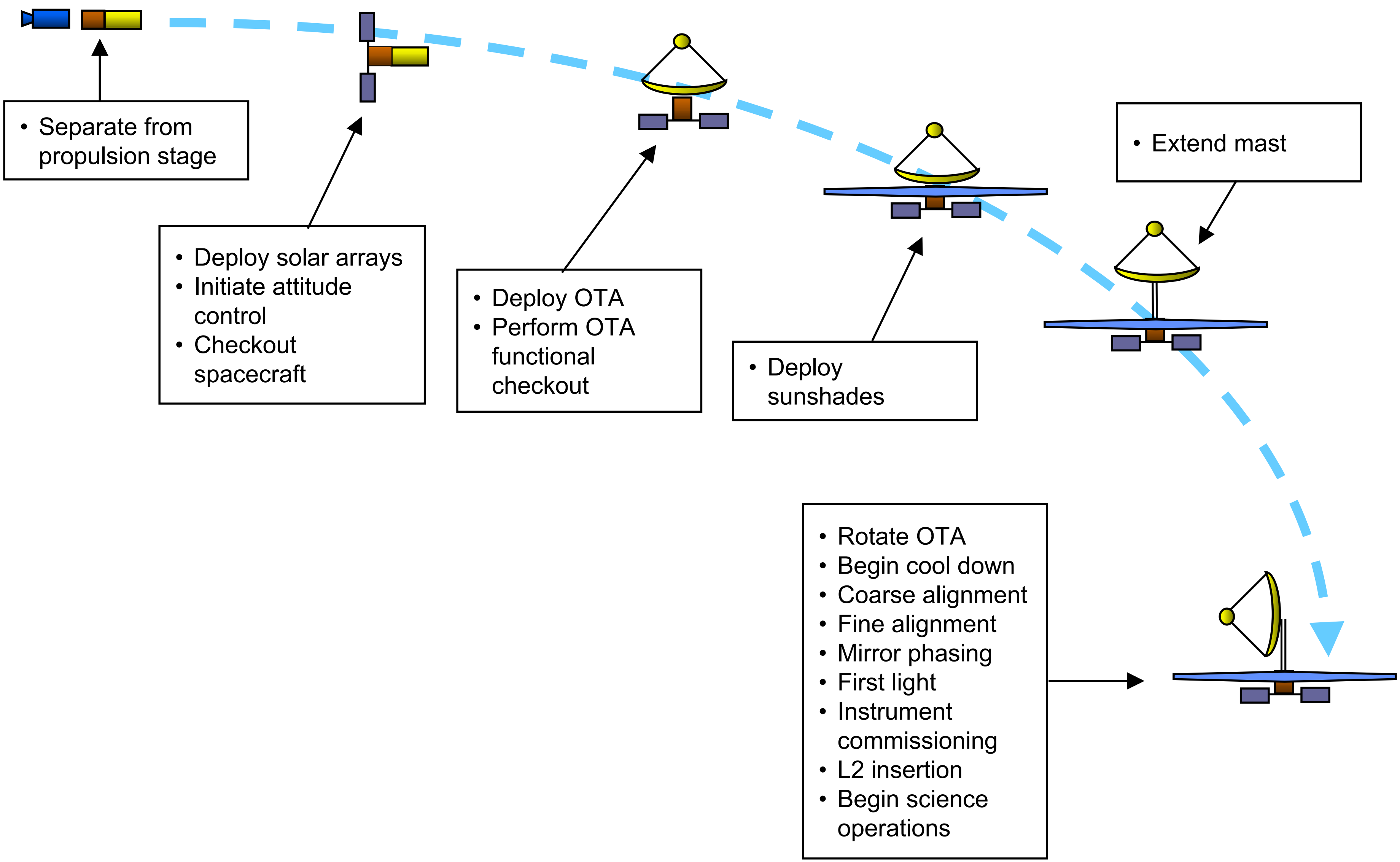


- Space Transportation System
- 5-m cargo bay
- Up to 24,400 kg to 400 km LEO
- Man-rating requirements on P/L
- Astronauts available to assist operations



Direct Trajectory Has Commissioning in Transit to L2 (Adapted From NGST)

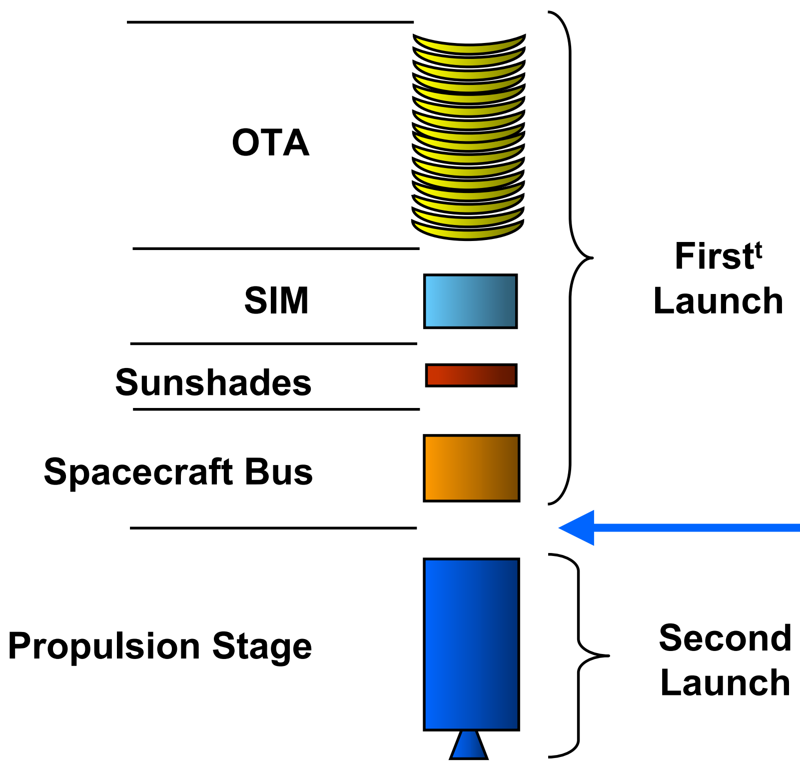
TRW



For Double Launch Need to Segment TPF at Simplest Interface

TRW

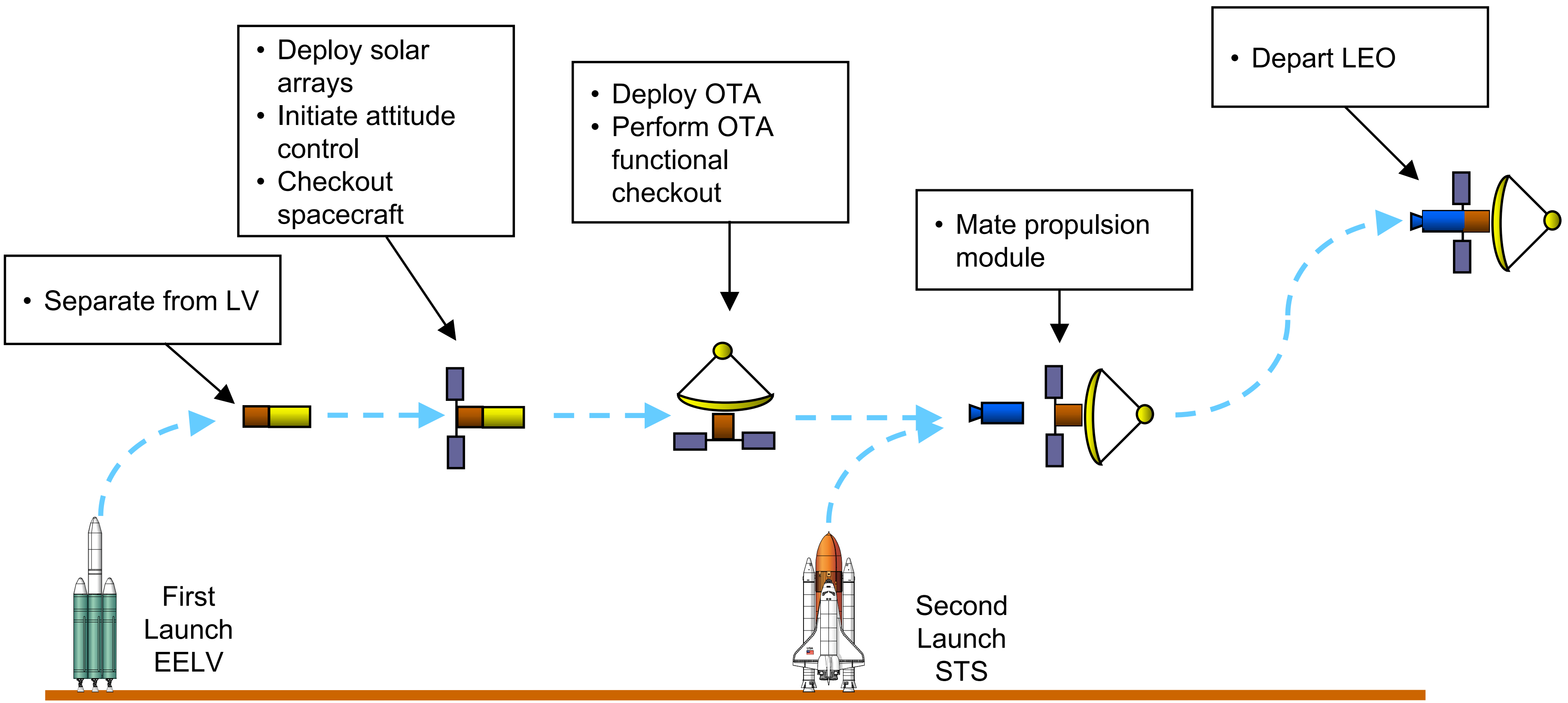
Major TPF Observatory Elements



- Place docking interface between spacecraft bus and propulsion stage
- Spacecraft bus provides attitude control in LEO
- Interface between propulsion stage and spacecraft does not involve precision (optical quality) alignments
- OTA can be checked out in LEO
- Propulsion stage will be separated from Observatory after L2 insertion anyway

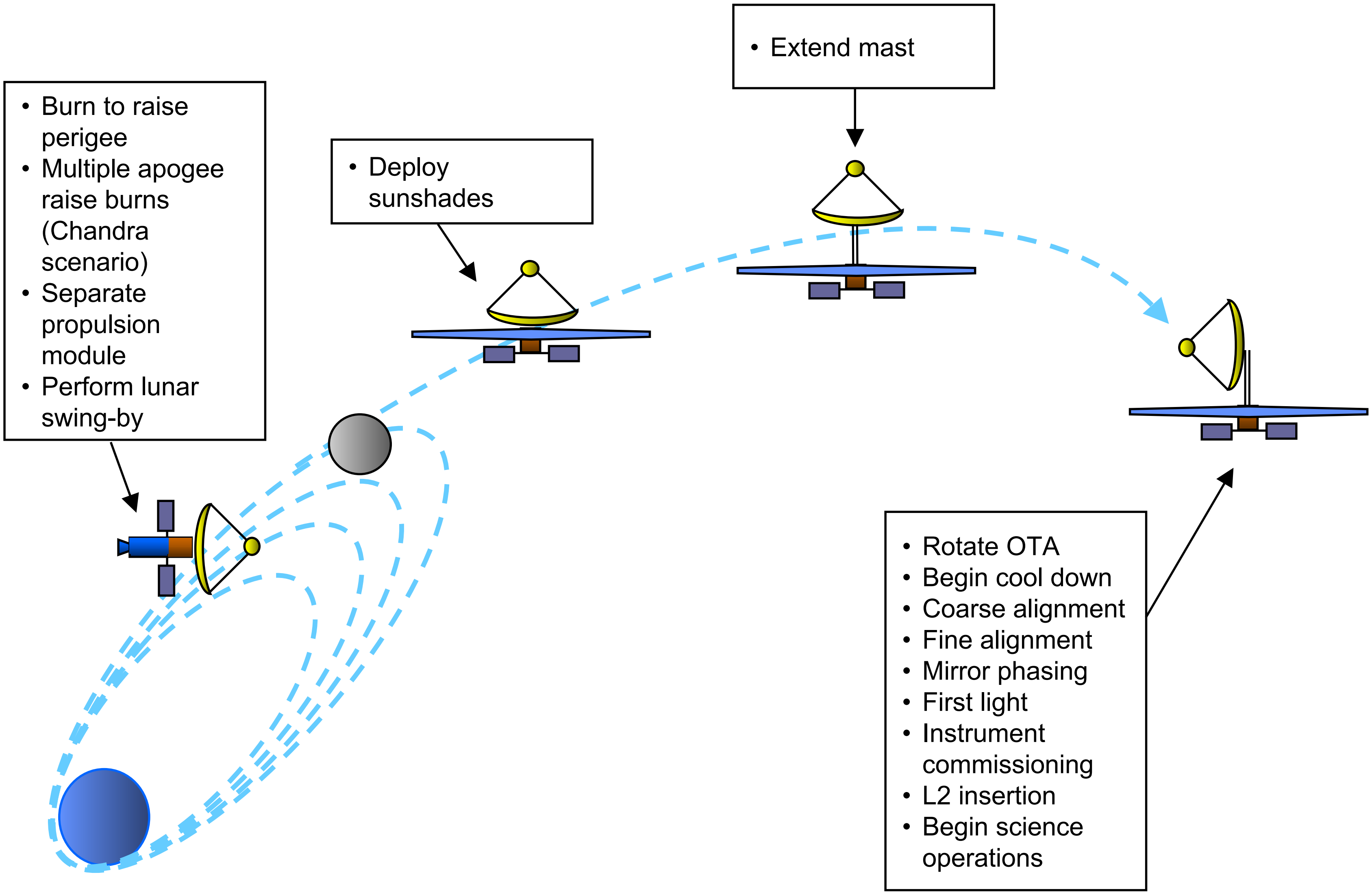
Two-Launch Option Has Commissioning Begin in LEO

TRW



Commissioning Activities Continue in Transit to L2

TRW



Propulsion Stage Selection Depends on Launch Scenario

TRW

Option	Cryogenic High-Energy Upper Stage	Bi-Prop Integral Propulsion Stage
Heritage	Based on Delta III Upper Stage	Based on Chandra and SIM IPS
Isp	450 sec	330 sec
Dry Mass	2,000 kg	2,400 kg
Propellant Mass	13,000 kg	18,700 kg
Peak Acceleration	0.9 g	0.039 g
LV	EELV only	EELV or STS
Implementation	Direct trajectory to L2; requires re-stowing of OTA and sunshades prior to insertion burn	Use multiple burns and lunar swing-by; low g-loading avoids requirement for re-stowing
Best Scenario	Ideal for Direct Trajectory	Ideal for Rendezvous in LEO

OTA Commissioning Approach Will Be Proven on NGST

TRW

- Set Primary Mirror segment piston/tip/tilt actuators to nominal (1 g) positions
- Set Secondary Mirror actuators to nominal (1 g) positions
- Commence cool down to SIM operating temperature
- Initial WFS&C commissioning
- Coarse alignment
- Coarse phasing
- Fine phasing
- Observatory first light
- After cool down to steady state, determine SIM operational readiness
- WFS&C commissioning adjustments as needed
- Re-phase optics prior to SIM evaluation and certification
- Final commissioning testing and certification of SIM and Observatory

Initial Instrument Commissioning Supports OTA Commissioning

TRW

- One instrument will be commissioned early (for example the guide camera) to support telescope commissioning
  - Power on electronics
  - Check telemetry
  - Power on FPA
  - Check telemetry and data
  - Take numerous dark frames to ensure detector is operating nominally (compare to ground data)
  - Open cover (if part of instrument) and illuminate detector
  - Check telemetry and data
  - Test all mechanisms
- After telescope is aligned
  - Calibrate guide camera once images from telescope are adequate
  - Measure PSF of known star
  - Calibrate plate scale across the field using double stars
  - Calibrate photometrically using known stars

Subsequent Instrument Commissioning Similar For All Instruments

TRW

- Spectroscopic instruments likely to use internal calibration sources
- Coronagraph will verify alignment capability to put star on the occulting spot
- Instruments with CVF require wavelength calibration to verify wheel position accuracy
  - Employ source with strong spectral features

Large Aperture TPF Can be Put in Space

TRW

- Stowing technology and lightweight optics make it possible to launch TPF in one or two launches
  - No special launch vehicle developments seem necessary
  - LEO rendezvous and docking activities can be supported by shuttle astronauts
- Commissioning procedures will be proven on NGST

Mission Operations

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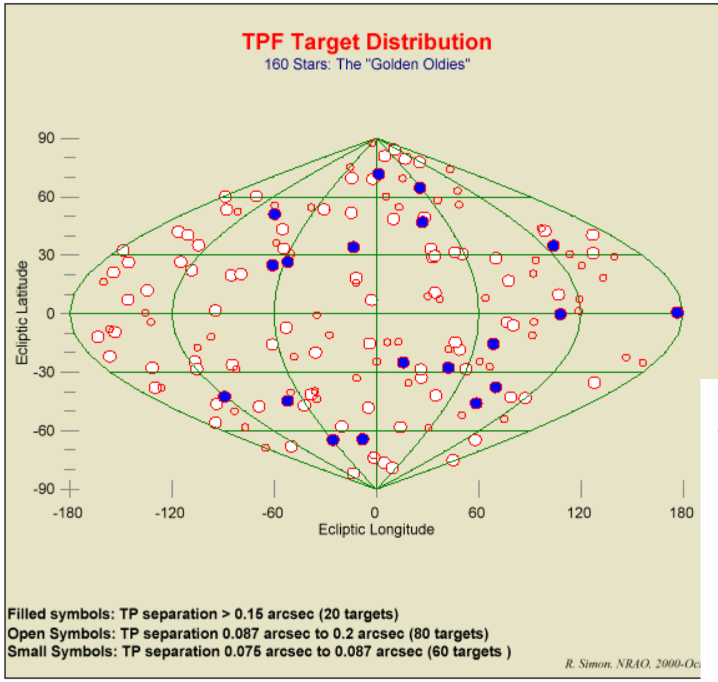
Mission Design Ensures Access to All Targets for Sufficient Time

TRW



- All sky access means all targets can be surveyed during the course of the mission
- >2 month access time per year allows revisits during the mission at appropriate intervals

	Integration time needed	
Target	**Detect**	**Characterize**
"average" system	20 hours	14 days (SNR=10) 28 days (SNR=25)
Earth/Sol @ 10 pc	2.4 hrs	42.3 hrs 265 hrs
150 sources (detection mission)	3×20×150 =1.0 yrs	N/A
30 "typical" sources (characterization mission)	3×20×30 = 0.2 yrs	25×14 days + 5×28 days = 1.3 yrs
	Total Integration time:	2.5 years

All targets can be surveyed during the mission limiting characterization to the closer sources (<25 pc)

Mission Timeline Estimation Includes Dependence on Target Type

TRW

- Planet Detection allocated ~1/4 of total mission time
  - 150 sources required
  - Typical integration time = 20 hours
  - Typical target separation ~15 degrees
- Planet characterization allocated ~1/4 mission time
  - ~30 sources required
  - Typical integration time = 14 days for R=20, SNR=10 (at 10 µm)
  - Typical integration time = 28 days for R=20, SNR=25 (O_3, CH_4 observations)
  - Typical separation ~40 degrees
- General Astrophysics allocated ~1/2 mission time
  - Estimate 1 target per day on average
  - Estimate typical separation ~10 degrees
  - Observations interspersed with planet finding and characterization mission to minimize slew times

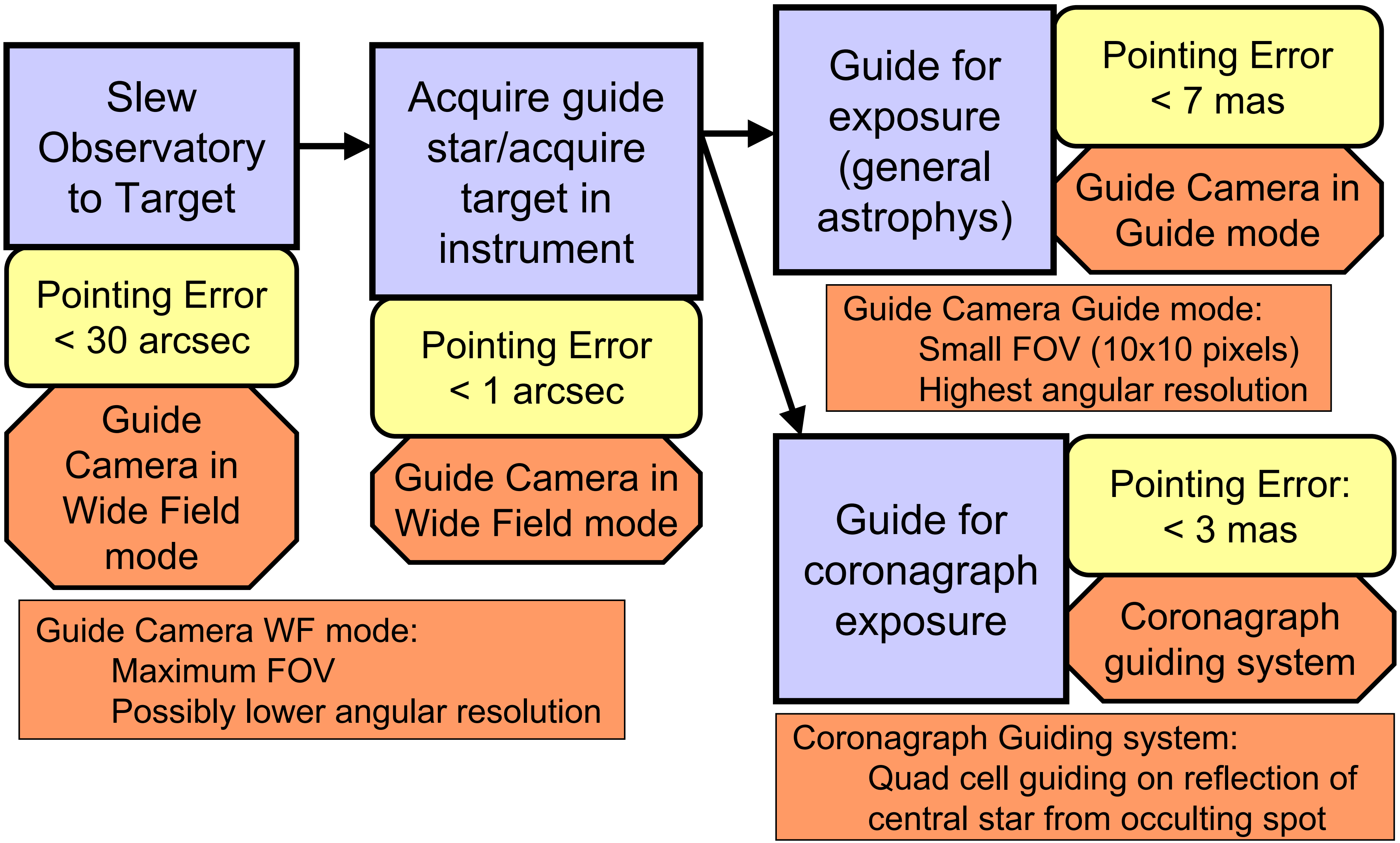
Mission Timeline Includes Overhead Allocations

TRW

- Slew and settle time
  - Estimate 1 hour slew + settle for a 10º motion
  - Increases marginally for larger slew distances
- Orbital maintenance is needed at L2
  - Estimate this action is required bi-monthly
  - Estimate 6 hours to complete these maneuvers
- Instrument calibration
  - Weekly to monthly to monitor changes in the FPA / electronics / optics performance
  - Requires slew to “standard” star
  - Take data in all filters of interest for all instruments that are used in previous and subsequent calibration intervals
  - Estimate ~6 hours for standard calibration sequence
  - Estimate ~12 to 24 hours for calibration sequence that includes updates to the primary mirror figure and deformable mirror settings

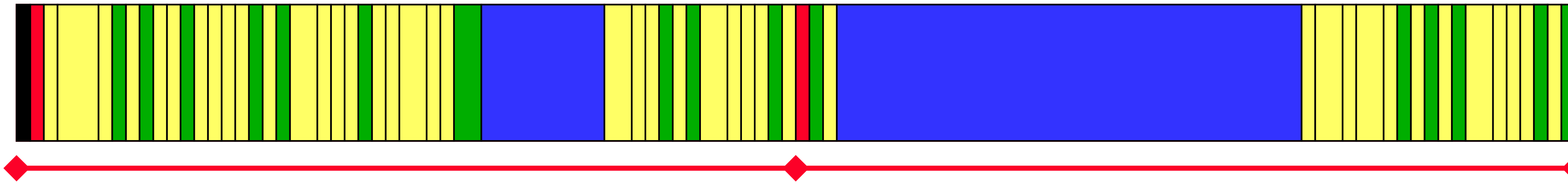
Target Acquisition Done in Steps to Meet Stringent Pointing Requirements

TRW



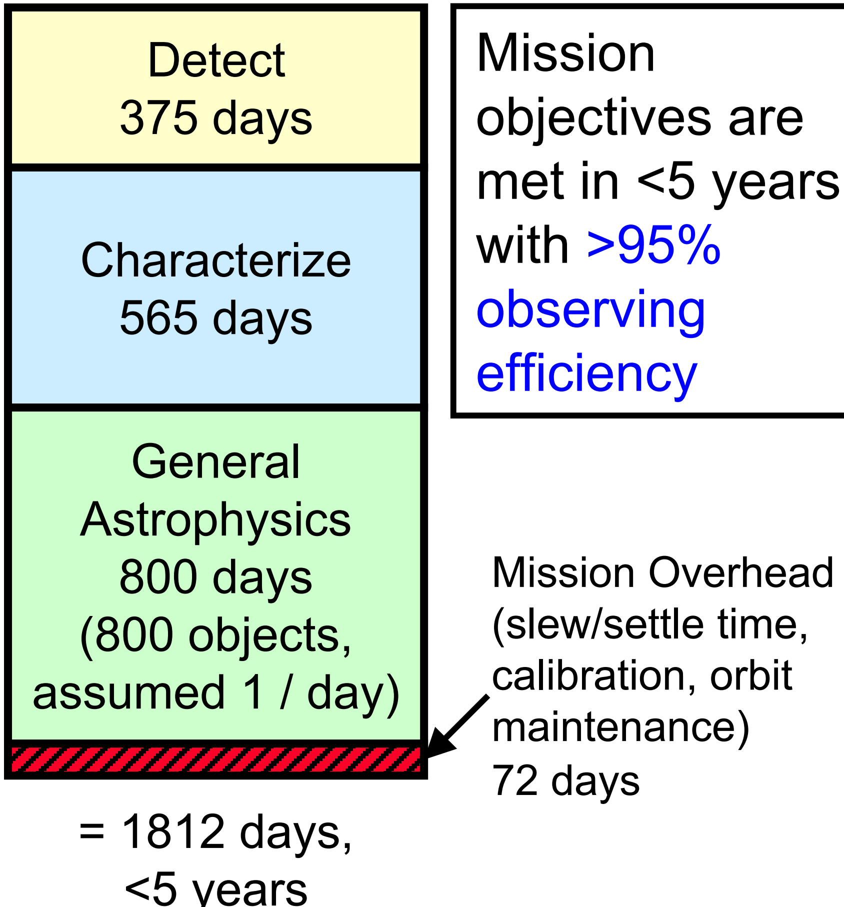
Mission Objectives Met During 5-Year Mission Lifetime

TRW



One Month Duration

- Planet Finding Mission
- Planet Characterization Mission
- General Astrophysics Mission
- Instrument/Telescope Calibration
- Orbital Maintenance



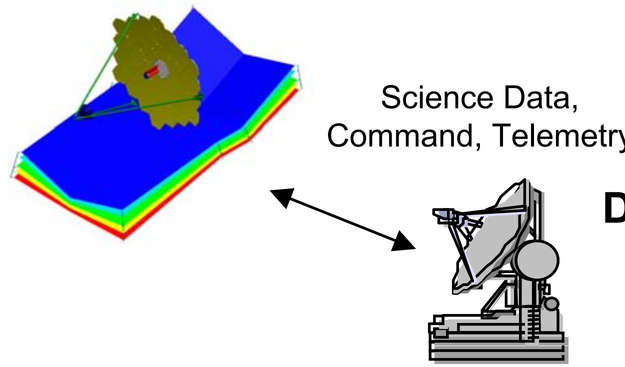
Mission objectives are met in <5 years with >95% observing efficiency

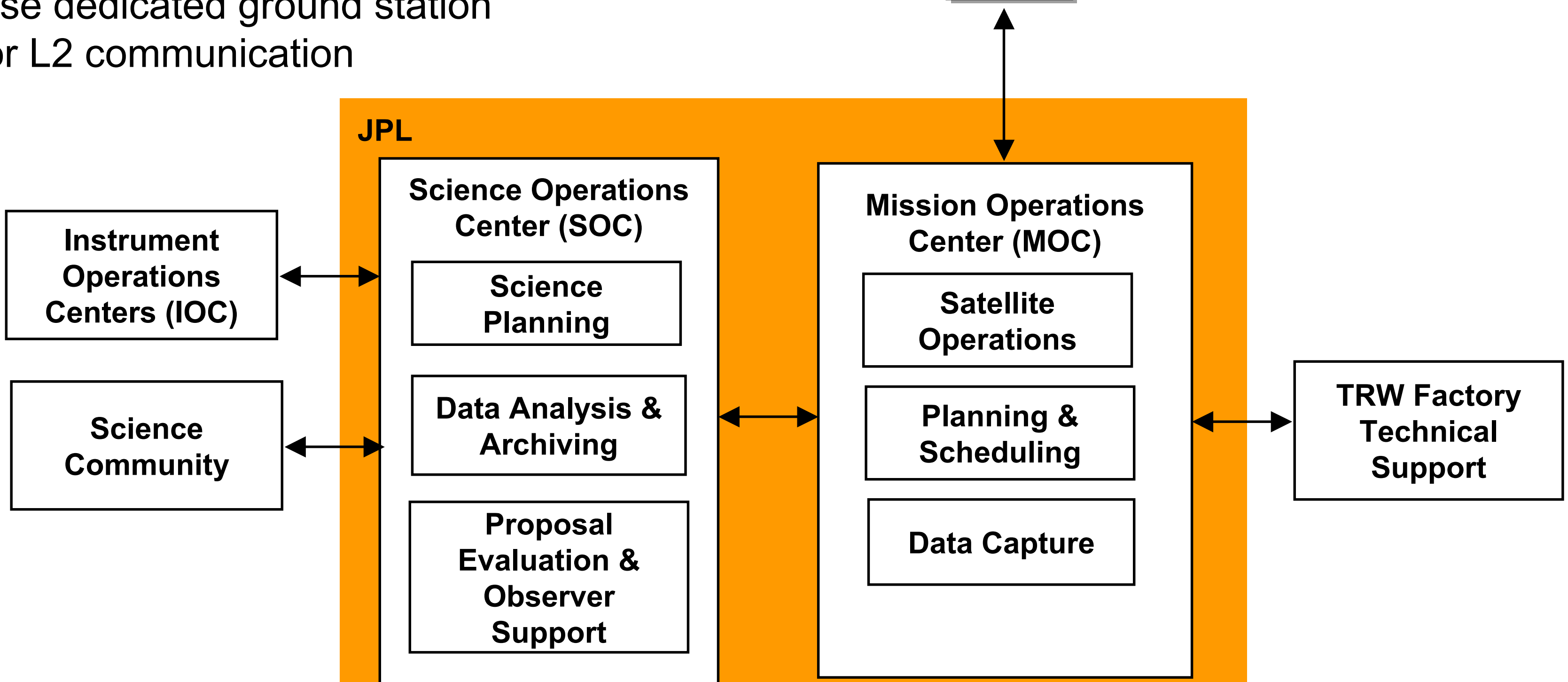
C&DH Streamlined to Enable Simple Communication Plan

TRW

Assumptions:

- Tasking done ~ 1 week in advance
- Data is sent down daily
- Commanding sent up ~ 2 times per week
- Use dedicated ground station for L2 communication





TPF Terrestrial Planet Finder

Coronagraph Architecture Provides Simple On-Orbit Operations

TRW

- Observatory operations are simple and will be validated with NGST
- Mission overhead time for this mission is estimated to be a small fraction of the overall mission (< 5% of mission time, not including commissioning or time to reach the L2 orbit)
- High accuracy pointing requirements will be met with layers of pointing control, shared between the spacecraft, the telescope, and the instruments
- Wavefront sensing and control algorithms will be validated using coronagraphic testbeds and on NGST for the primary segmented mirror
- Calibration of the instruments and data handling operations will be similar as for all previous visible and infrared astronomical telescopes in space (e.g., Hubble, SIRTF, NGST)
- A dedicated ground station for communication will simplify the data management functions and streamline the data processing pipeline
- Safehold operations only require protecting the mirror and front sunshade surfaces from the sun, reasonably simple to do in the benign L2 orbit for extended periods of time

Technology Roadmap

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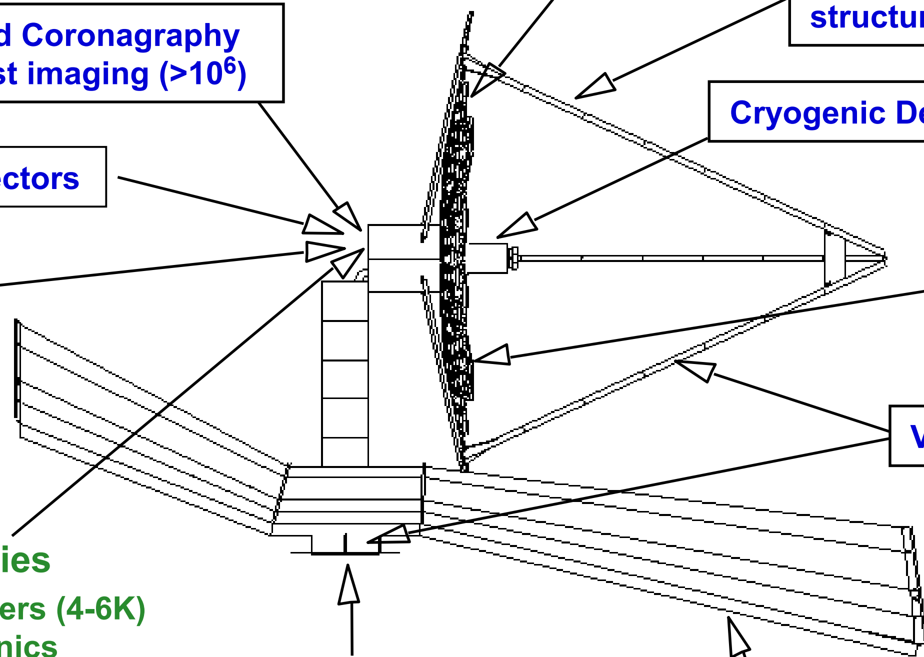
TRW

Topics

- In this section we:
  - Identify critical technology development needs
  - Identify “tall tent poles”
  - Assess difficulty of proposed technological approach
  - Identify alternative approaches
  - Show appropriate plans for developing critical technologies to the necessary readiness level
  - Provide metrics for evaluating technology development
  - Indicate other NASA programs require similar technology
  - Identify technologies that require space validation

Key Technologies

TRW



Enhancing Technologies

- Low vibration cryocoolers (4-6K)
- Cryogenic opto-mechanics
- Superconducting electronics
- Wavefront sensing and control

TPF Technology Readiness Levels

TRW

Technology	Current TRL	Development Risk	Being Developed By:
Large, lightweight Cryo-IR Optics	3	medium-high	NGST*
Low cost mirror production	4	medium	NGST*
Precision deployable structures	4	medium	NGST*
Low temperature materials	2	medium	NGST*
Active and passive isolators for vibration control	4	medium	SIM*
Cryogenic Dampers	4	medium	
High contrast imaging (>10^6)	3	medium-high	JPL-ETB
Wavefront sensing and control	4	medium	NGST*
Large format Si-As detectors	3	medium	SIRTF*
Large IR filters & broadband transmissive substrates	2	medium-high	SIRTF*
Low-vibration cryocoolers (4-6K)	4	medium	TPF, Con-X
Cryogenic opto-mechanisms	4	medium	SIRTF*
Cryogenic deformable mirrors	4	Medium	1 SBIR
Lightweight, compact, nanometer resolution actuators	4	medium	NGST*
Superconducting Electronics	3	medium	BMDO*
Light-weight deployable solar & thermal shields	4	medium	NGST*
High-torque/high capacity momentum wheels	3	medium-low	

"Tall Poles"

*** Additional technology development effort required**

"Evolution, not Revolution"

No technology breakthroughs are required

Other NASA Programs Require Similar Technologies

Technology	Life-Finder	Planet Imager	Constell-ation-X	FAIR	SPIRIT	SUVO	Interstellar Probe
Large, lightweight Optics	√	√		√	√	√	
Low cost mirror production	√	√	√	√	√	√	
Precision deployable structures	√	√	√	√	√	√	√
Low temperature materials	√	√		√	√		√
Active and passive vibration isolators	√	√	√	√	√	√	
Cryogenic Dampers	√	√		√	√		
High contrast imaging (>10^6)	√	√				√	
Wavefront sensing and control	√	√		√	√	√	
Large format Si-As detectors	√	√		√	√		
IR filters and substrates	√	√		√	√		
Low-vibration cryocoolers (4-6K)	√	√	√	√	√	√	√
Cryogenic opto-mechanisms	√	√	√	√	√		
Lightweight, compact actuators	√	√		√	√	√	
Superconducting Electronics	√	√	√	√	√		√
Deployable solar & thermal shields	√	√		√	√	√	√
Hi-torque/capacity momentum wheels	√	√		√	√	√	

Telescope Technologies

Telescope Technology Needs

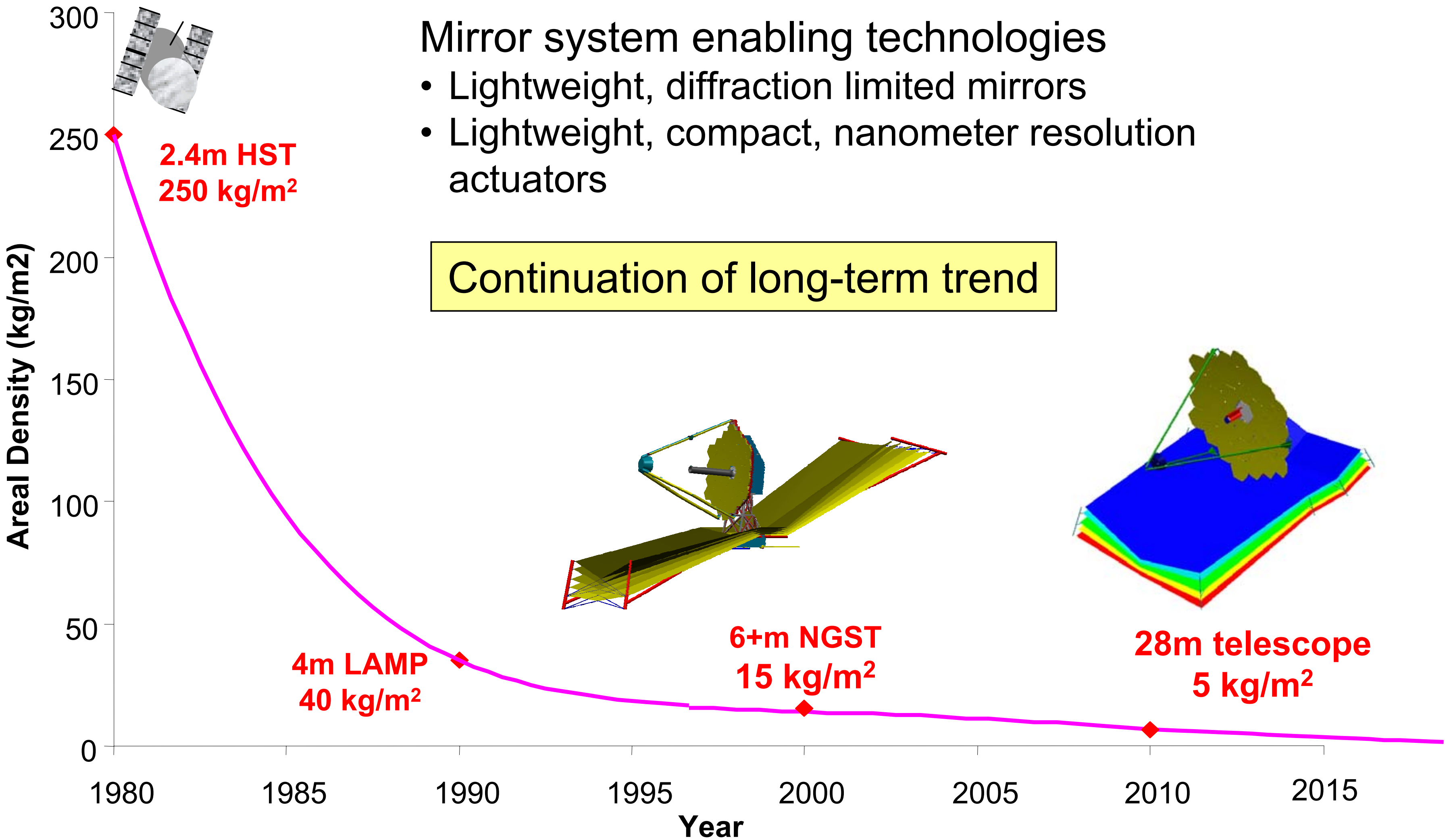
TRW

- Large, lightweight cryo-IR optics
  - 5 kg/m^2 areal density
  - 7 μm diffraction limited (3 μm goal)
  - Surface roughness < 100 Angstroms (30 Angstroms goal)
  - Mid-spatial frequency errors < 4 nm RMS
  - Lightweight, compact, nanometer resolution actuators
- Low-cost mirror fabrication
  - Thin replicated mirrors
  - Composite design
  - Mandrel production
  - Large segment production
- Low temperature materials
  - Cryo-compatible resins

Mirror Technology Advances

Mirror system enabling technologies
- Lightweight, diffraction limited mirrors
- Lightweight, compact, nanometer resolution actuators

Continuation of long-term trend



Composite Mirror SOA

TRW

- **Outer segments produced using replication techniques**
  - **COI 2-m FIRST demonstrator**
    - Cervit mold polished by University of Arizona
      - 0.25 μm surface accuracy; 100 Angstroms smoothness
    - Production from 2/99-8/99
    - Good wavefront performance
      - 2.32 μm RMS
      - After removing 1st 36 Zernickes, 1.00 μm RMS at room temperature
        - » 1.21 μm RMS at 200K vs. 0.2 μm RMS at 30K requirement
    - Design extrapolated to 3.5 m diameter at 11.4 kg/m^2
  - **CMA thin replicated mirrors**
    - Pyrex mold
    - 15 cm spheres at 0.79 μm RMS and 1.3 kg/m^2
    - 90 cm sphere at 1.7 kg/m^2
    - Surface roughness <10 Angstroms has been demonstrated.
    - Mid-spatial frequency errors <3 nm RMS has been demonstrated.
- **Composite mirror technology is on track to meet TPF requirements**

Technology Development Effort

TRW

- Resin studies
  - Currently using EX-1515, cyanate ester. 250F cure (low temperature); flight qualified
  - Investigate other resins (e.g., cyanate ciloxanes) to improve surface features and further reduce moisture effects and enhance toughness
- Composite design
  - Using resin system selected, design and demonstrate quasi-isotropic layup that will provide required CTE, CME, stiffness and strength
- Mandrel production
  - Lower cost through inexpensive metrology
    - Leverage Bauer metrology or surface profilometry
  - Segmented mandrel production and joining without discontinuity
- Large segment production
  - Demonstrate required figure and control on large segment
  - Develop production plan to achieve 36 segments in 45 months

Telescope Technology Roadmap

TRW

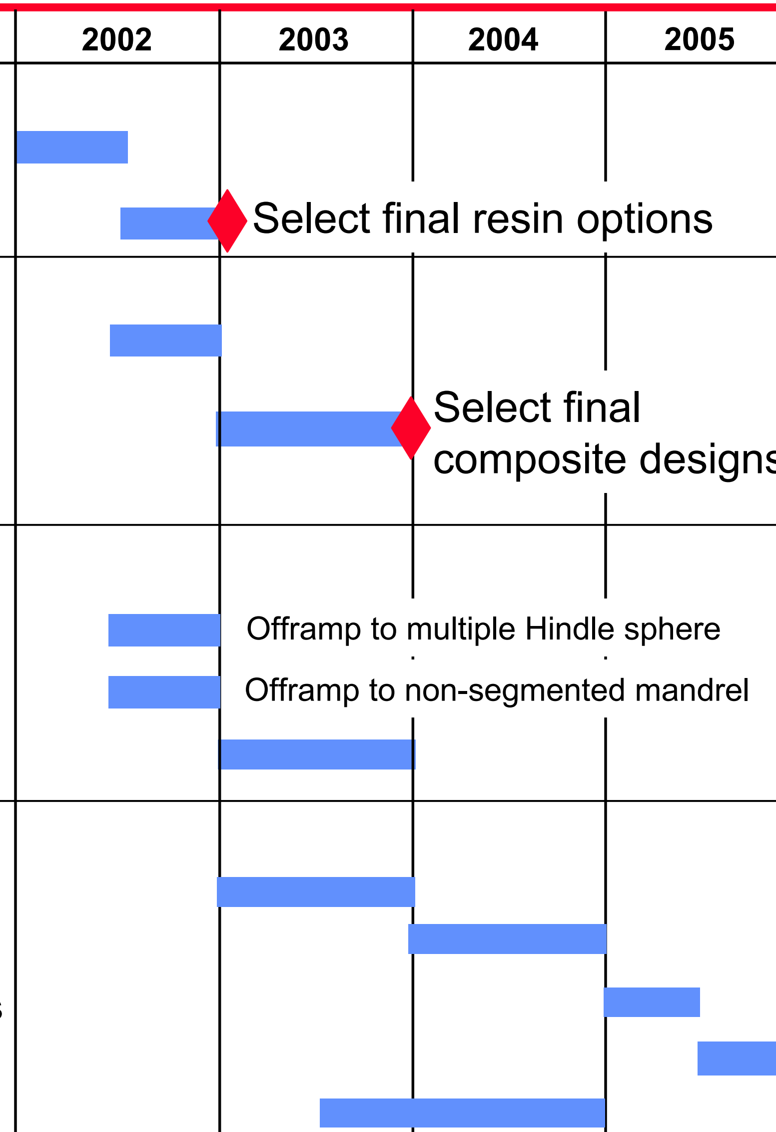
Activity Name

Resin studies
- Survey current resin properties
- Develop surface production method

Composite design
- Design candidate layups; test coupons
- Layup panels to demonstrate material properties, uniformity, and surface roughness

Mandrel production
- Metrology definition
- Demonstrate mandrel joining techniques
- Produce full segment mandrel

Large segment production
- Actuator and reaction structure design
- Full-scale replication
- Demonstrate mid and high spatial frequencies
- Cryogenic test
- Large-scale production studies



Spacecraft Technologies

Vibration Control Needs

TRW

- Lower natural frequency of TPF requires more vibration suppression than SIM and NGST
- Active and passive vibration control with cryogenic damping
  - Passive isolator attenuation 40 dB at 10 Hz
    - Active augmentation additional 20 dB below 10 Hz
    - Micro-Newton force sensors to measure low frequency, low vibration levels ~10 m-N resolution
  - Cryogenic damping in the telescope >3% at 20K

Current SOA: SIM Dual-Stage Passive Vibration Isolation

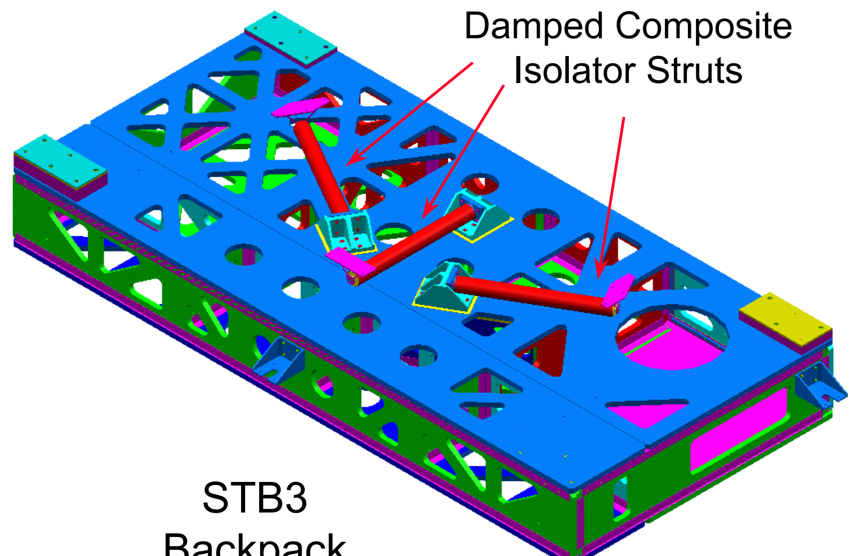
TRW

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 pathlength control at 100 Hz

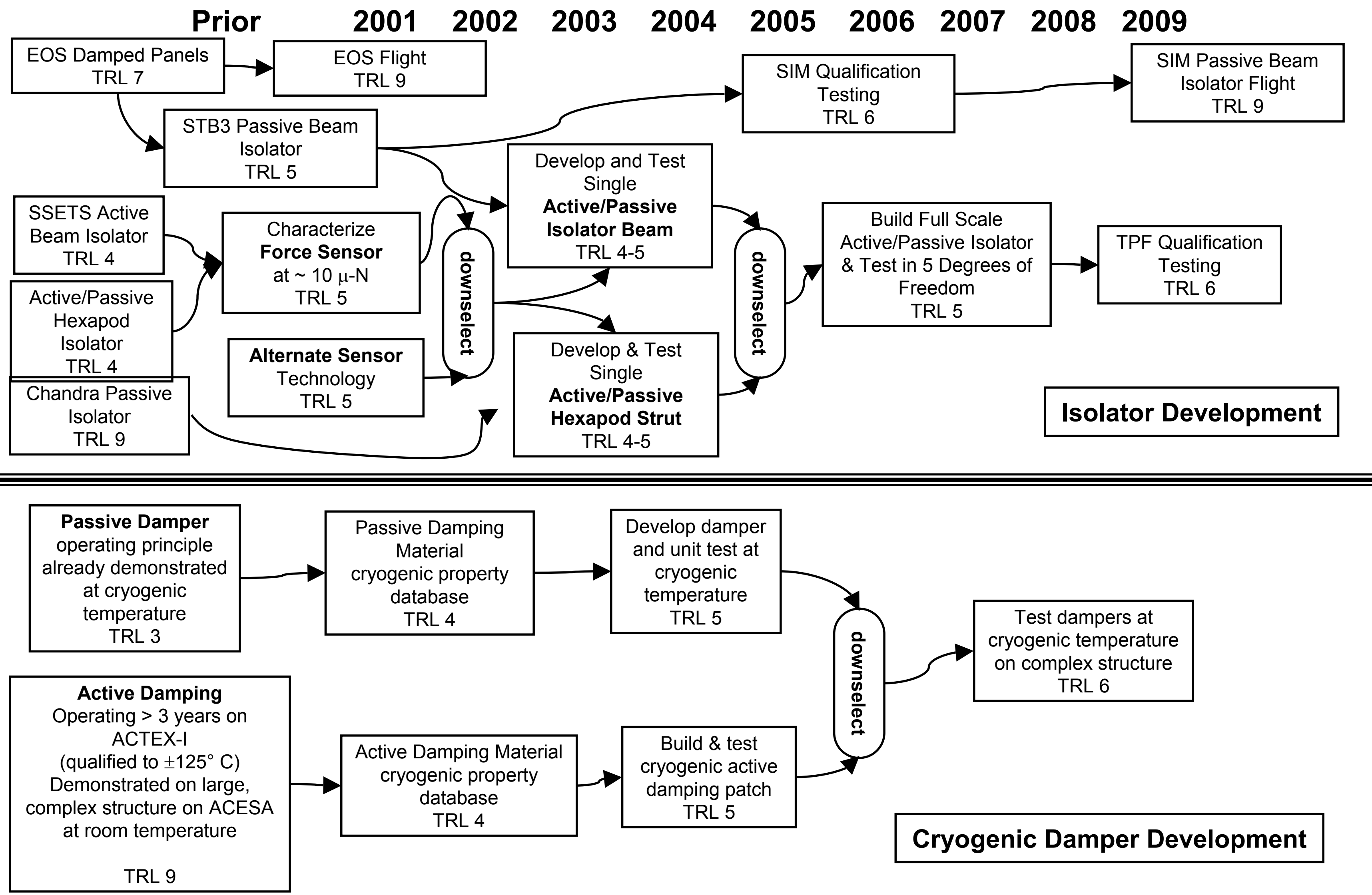
Second Stage at Backpack

- 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



Vibration Control Technology Roadmap

TRW



Spacecraft Enhancing Technology Needs

TRW

- Lightweight deployable solar and thermal shields
  - 100:1 packaging efficiency
  - <0.15 kg/m^2 areal density
- High torque/high capacity momentum wheels
  - Torque >1 N-m
  - Momentum storage >400 N-m-s

Current SOA

- Sunshades
  - Mechanically deployed (AstroMesh) antennas have areal densities <0.25 kg/m^2
  - Inflatable antennas have demonstrated areal densities < 0.35 kg/m^2
  - Lower mass (and much lower inertias) is highly desirable
- Reaction Wheels
  - Teldix RDR-68 wheel on EOS, Chandra
    - Torque = 0.14 Nm, Momentum Storage = 68 N-m-s
  - Largest wheels from Honeywell, HR-16X
    - Torque = 0.2 Nm, Momentum Storage = 150 N-m-s
  - HST wheels no longer in production

Sunshade and Reaction Wheel Technology Roadmap

TRW

2002 2003 2004 2005 2006 2007 2008 2009 2010

TPF Technology Review

Prelim Designs

Detailed Designs

PDRs

CDRs

Engineering Models

TRL 3 4 5 6 7

Instrument Technologies

High Contrast Imaging Technologies

- Deformable Mirrors
  - Current state of the art is modules with 441 actuator elements on a 1 mm pitch driving a thin silicon facesheet with a stroke of ~ 0.6 microns
  - The TPF design goal is ~200 x 200 actuators on a 2.5 mm pitch a stroke of ~4 microns
- Wavefront Sensing and Control
  - Phase and wavelength diversity methods are being developed for telescopes such as Keck, NGST, and other adaptive optics systems
  - Layers of control between the primary mirror, secondary mirror, DM, and any other controlled mirrors will need to be validated
- Infrared apodized occulting spots on highly transmissive and non-scattering substrates
  - 10^{-8} transmission occulting spots with a gaussian taper deposited on optical substrates have been demonstrated.
  - IR substrate materials need to be validated, but similar apodization techniques should be applicable

Instrument Technology Needs

TRW

- Large format SiAs detectors
  - Formats > 512 x 512 pixels
  - Dark current < 30 e-/second at 10K
  - Readout noise < 100 e-
- Large IR filters and broadband substrates
  - 10 cm x 10 cm filters
  - 3 to 28 microns
  - ~20% bandpasses
- Other technologies
  - Cryocoolers
  - Cryogenic mechanisms for filter wheels and occulting spots
  - Low-power, cryogenic electronics for FPA signal conditioning
  - Low power drivers for filter wheels and other mechanisms
  - High speed, large format detector for guide camera

Instrument Technology SOA

TRW

Large format Si:As detectors:

- SIRTF will fly 128^2 (MIPS, IRS) and 256^2 (IRAC) formats
- SIRTF IRAC devices demonstrate low readout noise (<50 e^- with CDS) and low dark currents (<5 e^- per second at 5K)
- 512 x 412 devices demonstrated*
- Mean QE>45% demonstrated for SIRTF IRAC devices
- 1024^2 formats under development for NGST*

High frame rate, large format detectors for guide camera:

- Up to 1024 x 1024 HgCdTe and InSb devices currently available with >8 Mpixels/second per output pixel rates with multiple ports for 30 to 60 Hz full frame operation
- Windowable devices also available
- Development needed for 2048^2 devices with 1-30 Hz full frame rates and ≤32 outputs

Large infrared filters and substrates:

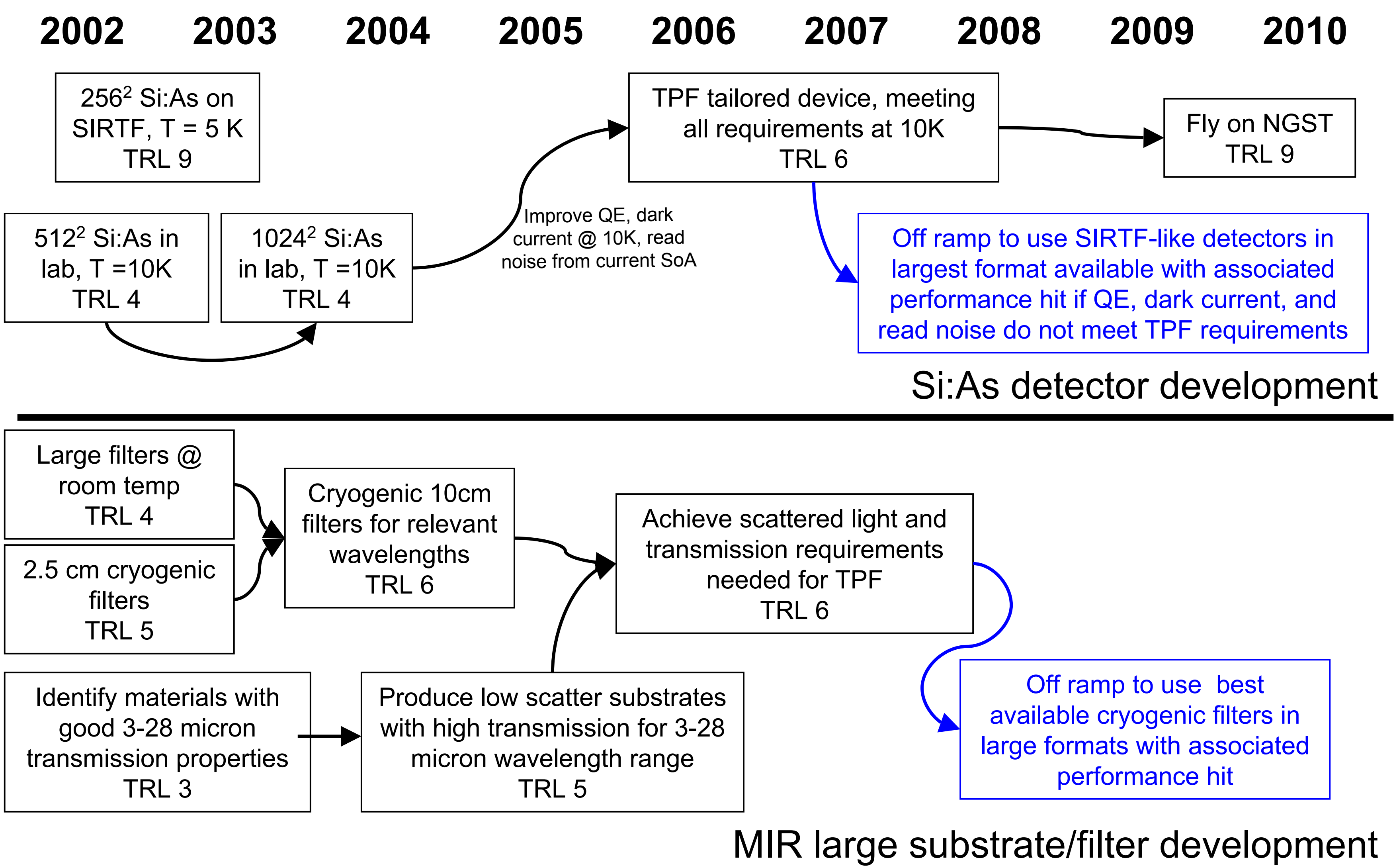
- 1-inch filters common for mid infrared applications in ground based astronomy
- Typical materials have large scatter functions which cannot be allowed in the coronagraph
- OCLI data sheets show filters up to 15.5 μm with >80% transmission for 10% bandwidths in up to 150 mm diameters

Dispersive elements:

- Dispersive gratings for SIRTF IRS have much higher dispersion (corresponding to an R=60-120) than needed for TPF (R~20)

*Love et al., "Infrared Detectors for Ground-Based and Space-Based Astronomy Applications," 2000, Raytheon IRCoE

Instrument Technology Roadmap



Low-Vibration Cryocoolers

Cryocooler Technology Needs

TRW

- Low-vibration cryocoolers
  - Cooling power > 10 mW
  - Cold tip temperature 4-6K
  - Temperature accuracy ±0.5K, repeatability of ±0.2K
  - 50K pre-cooling
  - Cooler mass < 30 kg
  - Input power < 50 W
  - Lifetime > 10 years
  - Self induced vibration level < 100 mNp (0-500 Hz)

Cryocooler State of Art

- **Long life, flight cryocoolers capable of operating as low as 30K are in orbit** (TRL 9)
  - Pulse Tube, Stirling
- Next generation coolers to **10K** and staged **coolers are being developed** by AFRL (TRL 4)
  - Stirling, Pulse tube
- **Coolers capable of reaching 6K** (TPF requirement) **have been demonstrated** in lab (TRL 4)
  - Hybrid Stirling -JT, Turbo Brayton
- Advanced Cryocooler Technology Development Project (**ACTDP**) from Code S and JPL **is designed to meet TPF needs**

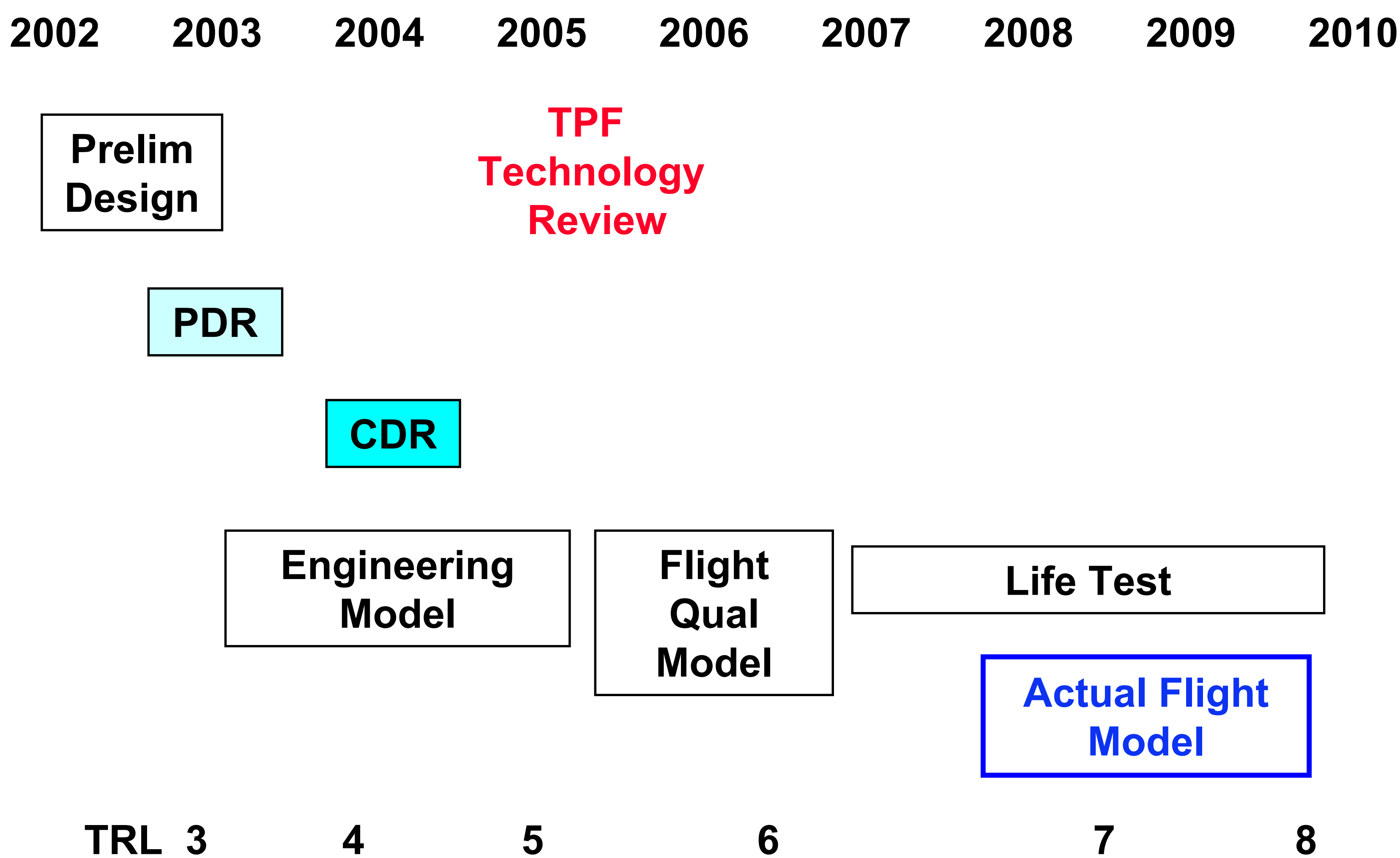
Cryocooler Development Options

TRW

- Development of **staged low temperature coolers** (e.g., 18K and 6K)
  - **Regenerative** coolers - Pulse Tube, Stirling
    - Low temperature regenerators
  - **Joule Thomson** coolers or cooling stages
    - Long life compressors, contamination control, life demonstration
  - **Turbo Brayton**
    - Low temperature heat exchangers, tiny rotors, contamination control, life demonstration

Cryocooler Technology Roadmap

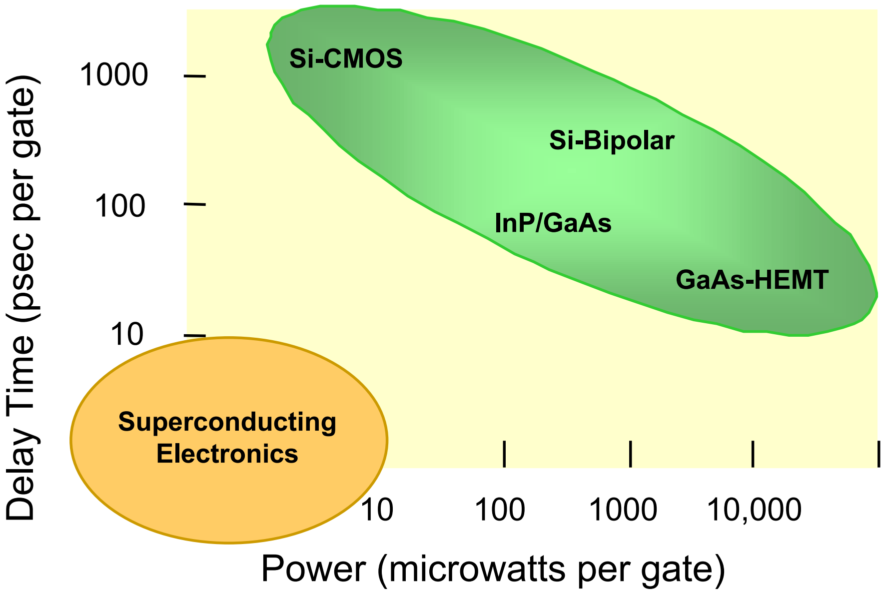
TRW

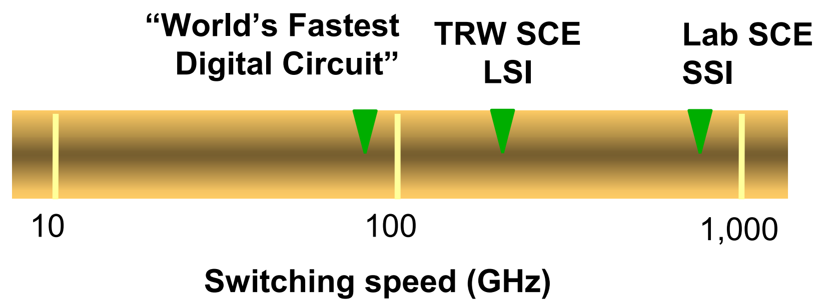


Superconducting Electronics

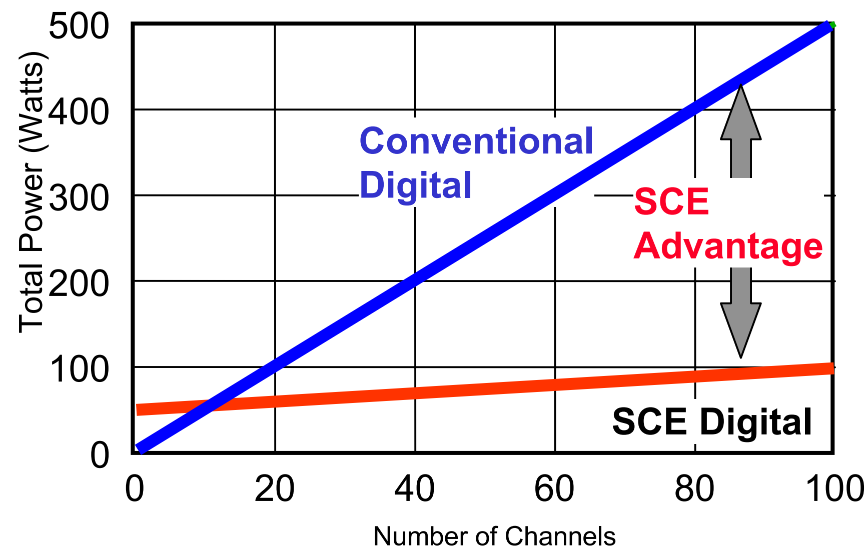
Superconducting Electronics (SCE): High Performance at Low Power

TRW





SCE advantage grows as complexity grows



Superconducting Technology Needs

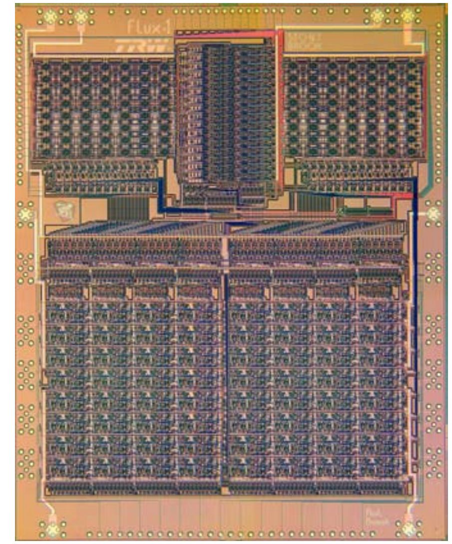
TRW

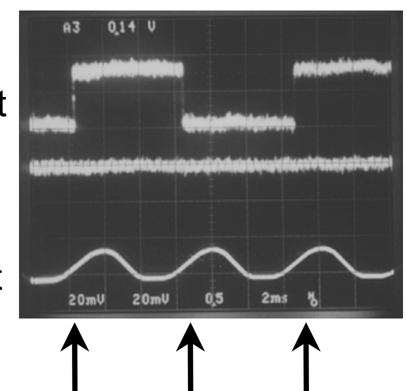
- 10K Niobium Nitride (NbN) integrated circuits for mid-IR focal plane array readout
  - Multiplexers
  - Analog-to-digital converters
  - Line drivers
- 70 K YBCO ($YBa_2Cu_3O_7$) integrated circuits for instrument data processing
  - Instrument control
  - Level conversion
  - Rate buffering
  - Frame addition and noise rejection
  - Data formatting

SCE State of the Art

TRW

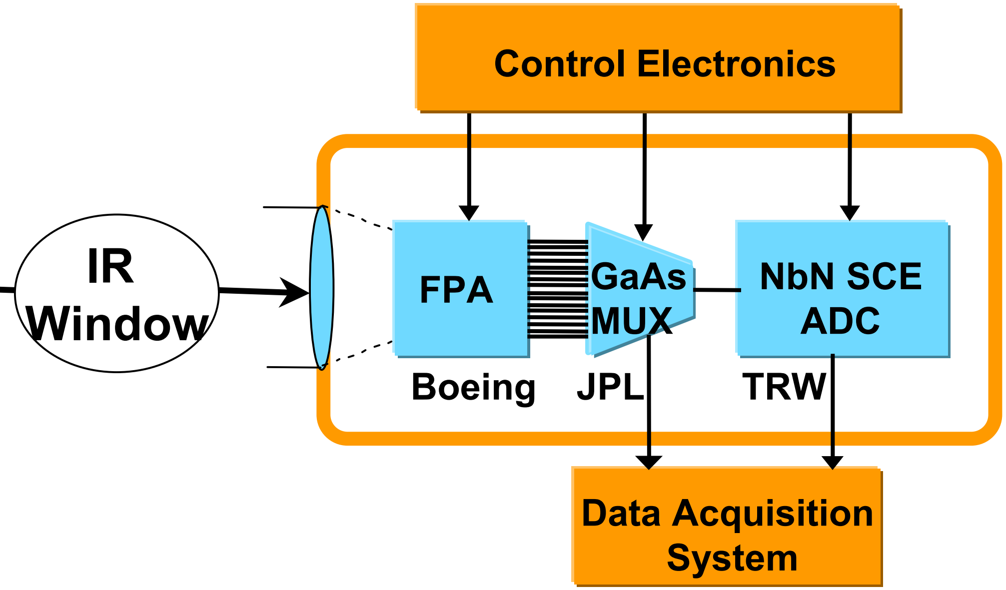
- <6K Niobium medium-scale integrated circuits (TRL4)
  - 10.65 mm x 13.2 mm chip
  - Power dissipation ~ 5 mW at 4.5K
  - 70,000 junctions, 5,000 gate equivalent
  - 5 GByte/sec inter-chip data transfer
  - 40 GOPS peak computational capability (8-bits at 20-GHz clock)
- Digital HTS circuits have been demonstrated at low integration levels (TRL3)
  - Flip-flop operation at 65K
  - Circuit under test contains 11 junctions
  - Toggle flip-flop changes state every rising edge of input
- TRW HTS Space Experiment on ARGOS was 100% successful



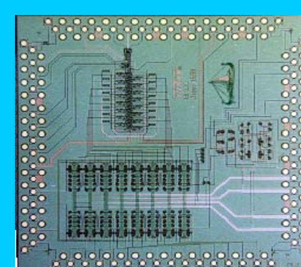


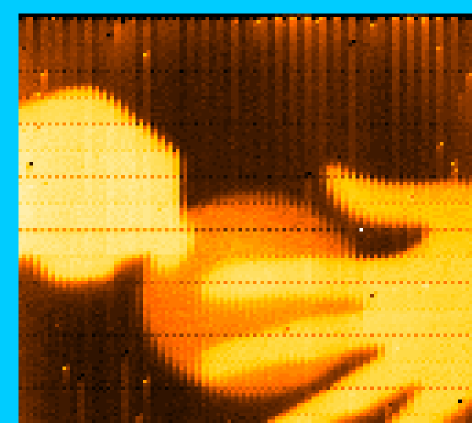
Cryogenic IR Camera with NbN ADC Produces Mid-IR Images

TRW



2000 Image

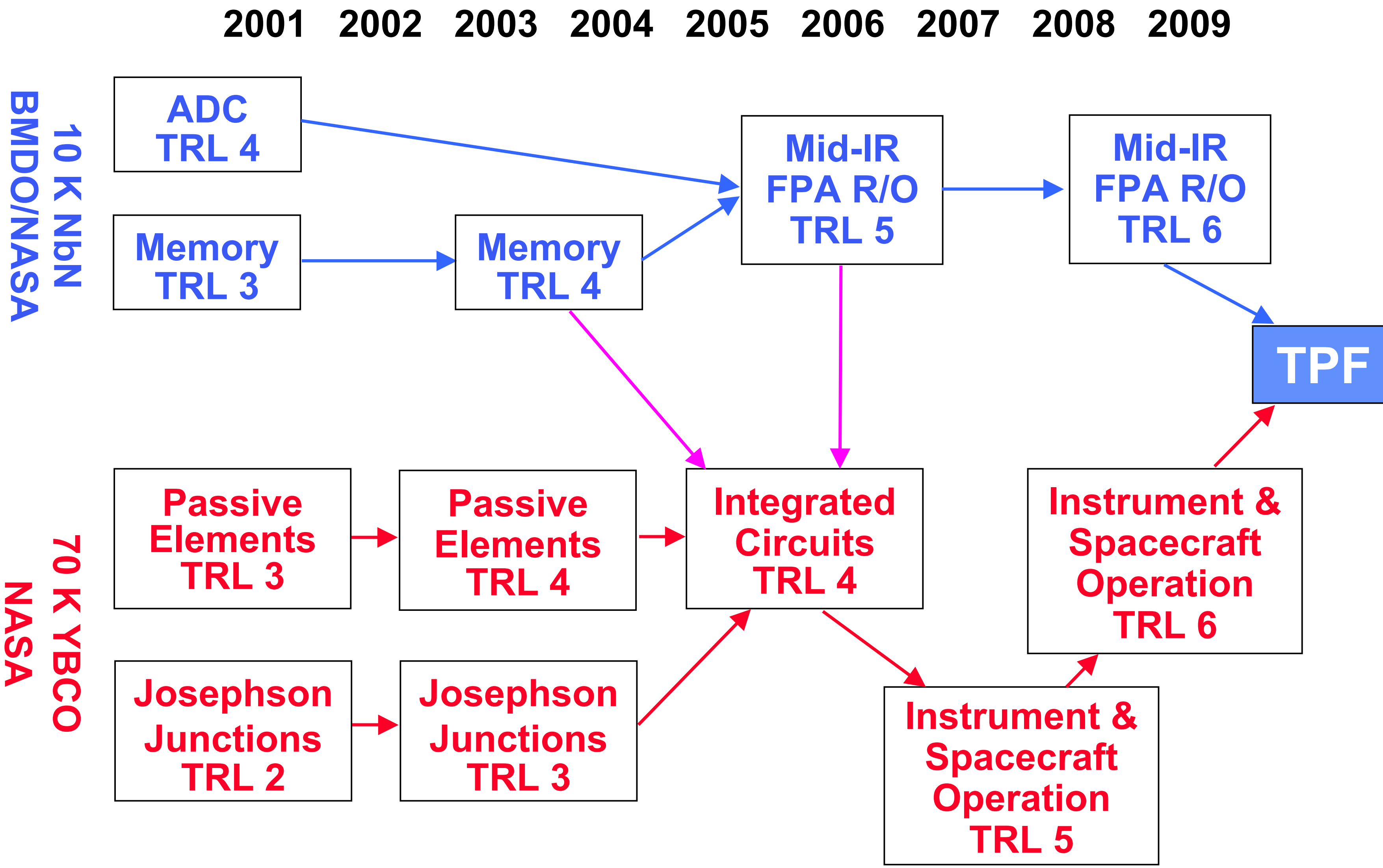




NbN IC (5 mm × 5 mm): 16 bit ADC + digital multiplexer + bit serial subtraction circuit

SCE Technology Roadmap

TRW



Deployable Optics Testbed

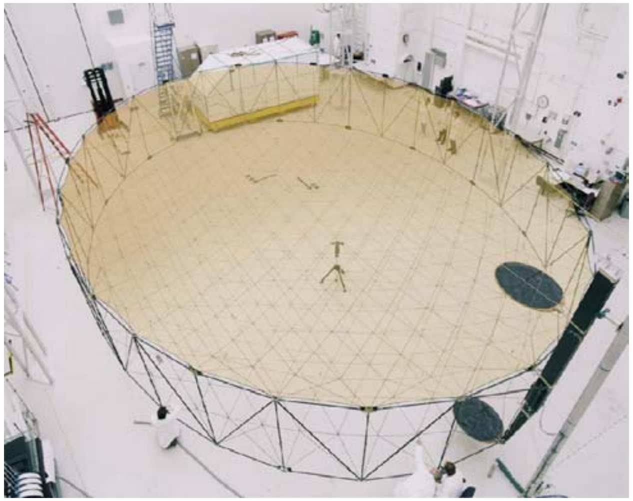
Testbed Objectives

TRW

- Demonstrate deployment concept for optical applications
  - **HARD concept selected from trade study**
- Further develop the primary mirror deployable structure technology
  - **Unique to the TPF mission**
- Address key issues
  - **Cryogenic temperature compatibility (for TPF, LifeFinder, etc.)**
  - **High reliability**
- Validate designs and analysis
  - **Test program**
- Demonstrate growth capability
  - **Add segments, mirrors, actuators, SMSS, ISIM, etc.**

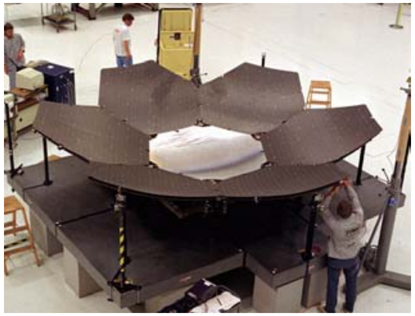
Continued Innovation and Advancement of Deployables

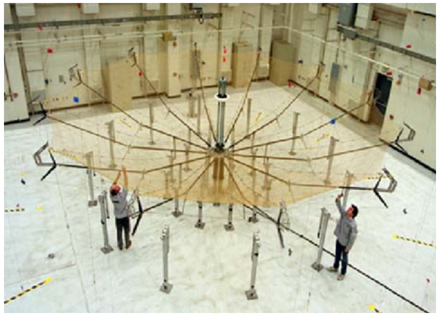
TRW



12-m AstroMesh Thuraya Reflector

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





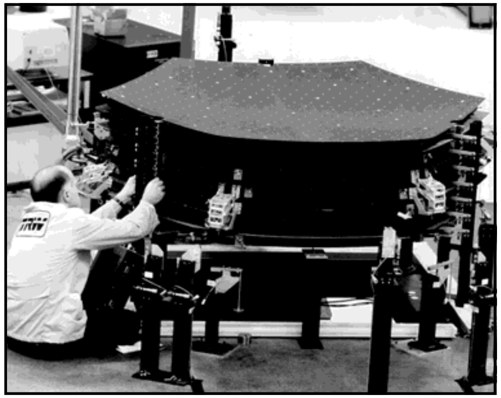
9.2-m PAMS Reflector

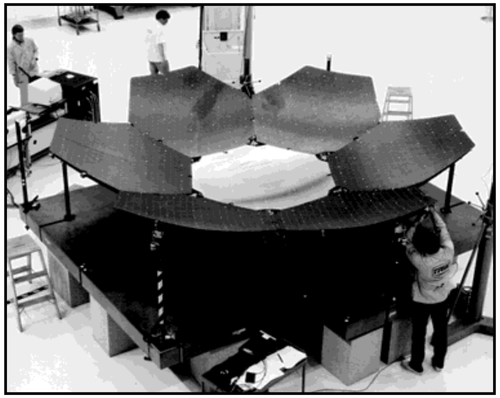
5-m PAMS Reflector

5-m HARD Reflector

High Accuracy Reflector Development Program (HARD)

TRW

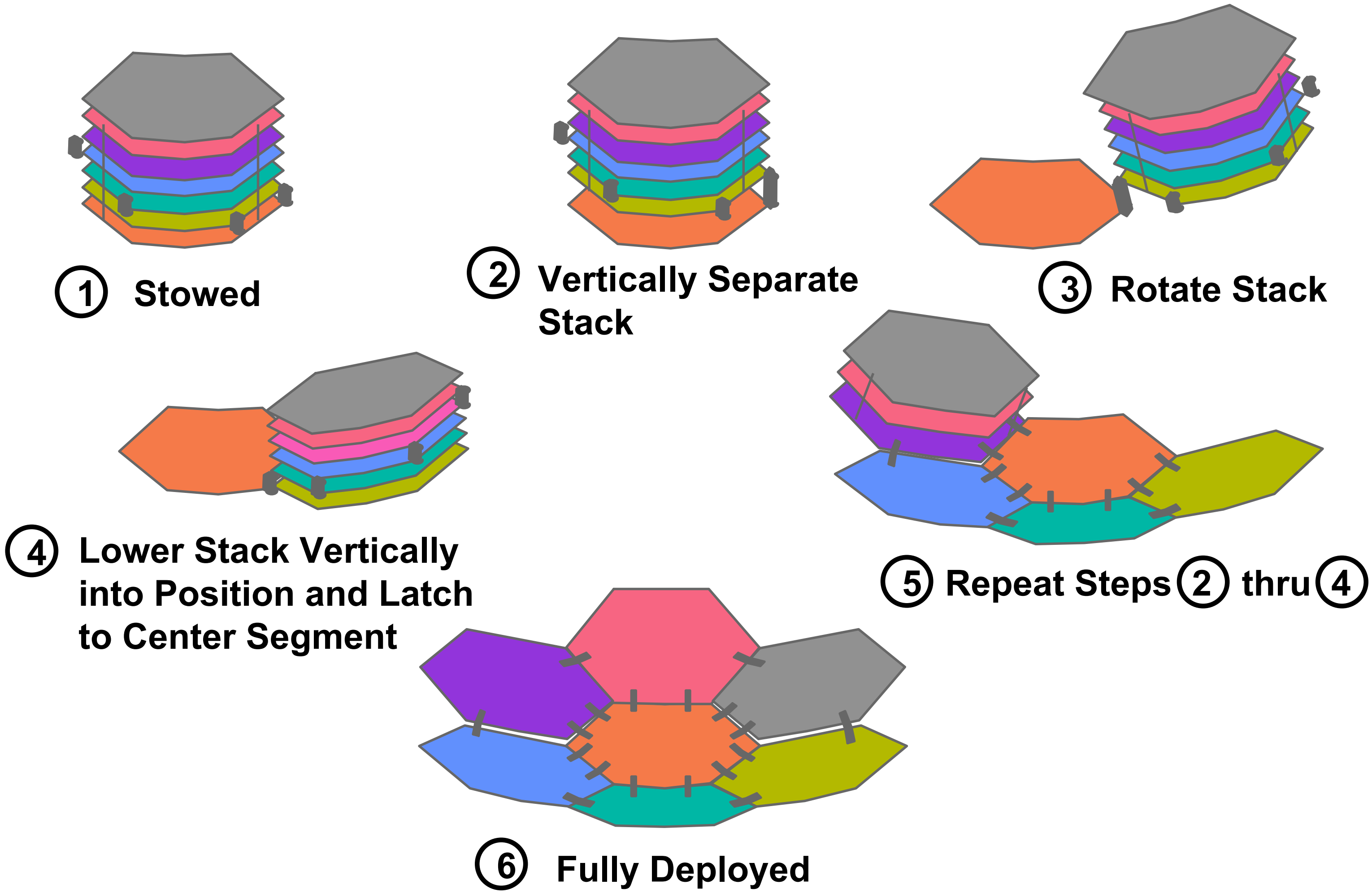




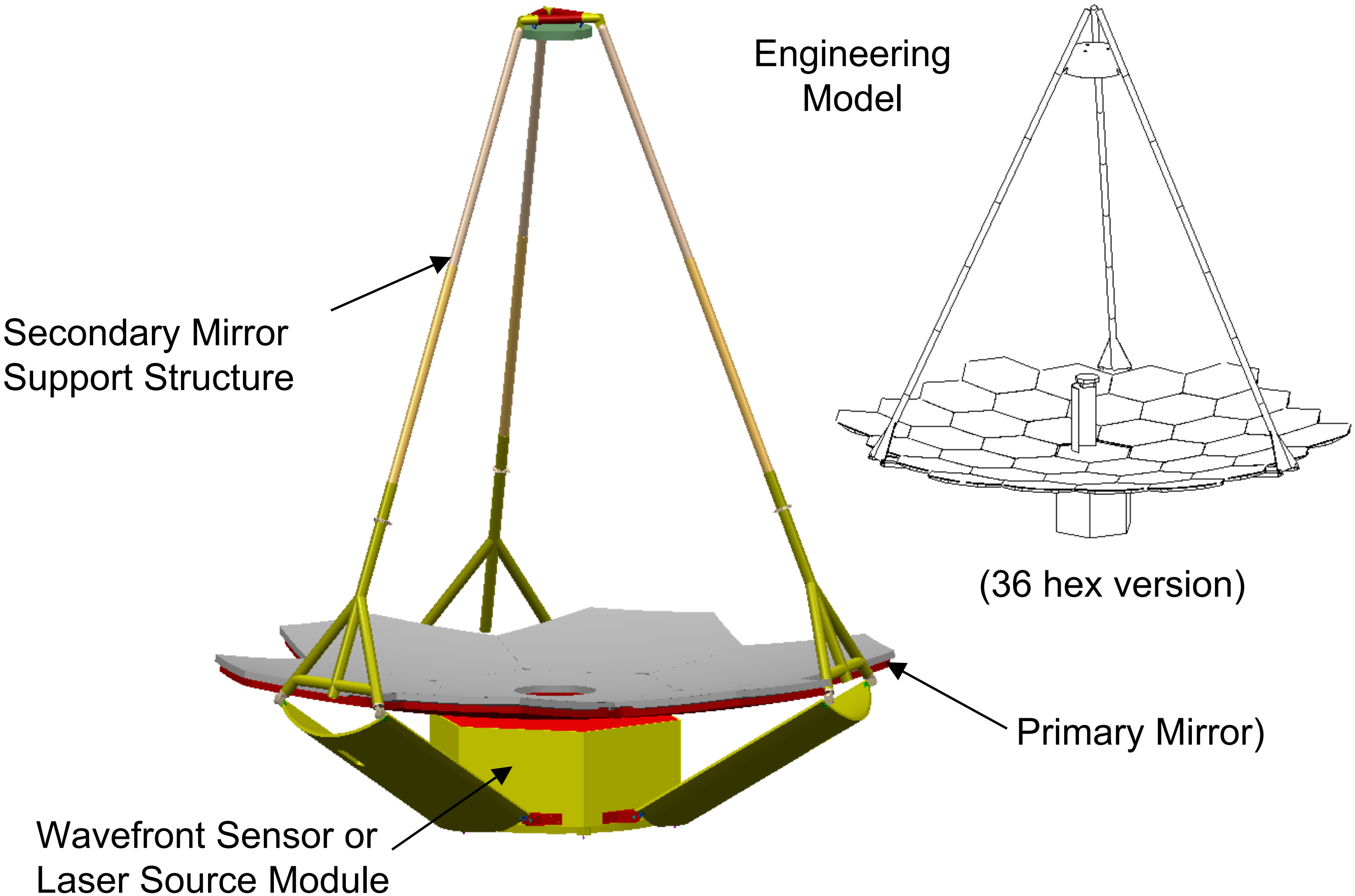
Stowed **Deploying** **Deployed**

- 15-ft. (4.6 m) aperture, deployable, solid surface reflector, 200 microns RMS
- Total weight 100 lb. (45.4 kg) including subreflector and boom (panel areal density ~3.33 kg/m^2)
- Stows to 2 ft. (0.61 m) tall by 5 ft. (1.52 m) diameter
- 1.2 dB gain loss at 60 GHz verified in nearfield
- Structural integrity verified by test program

Reflector Deployment Sequence

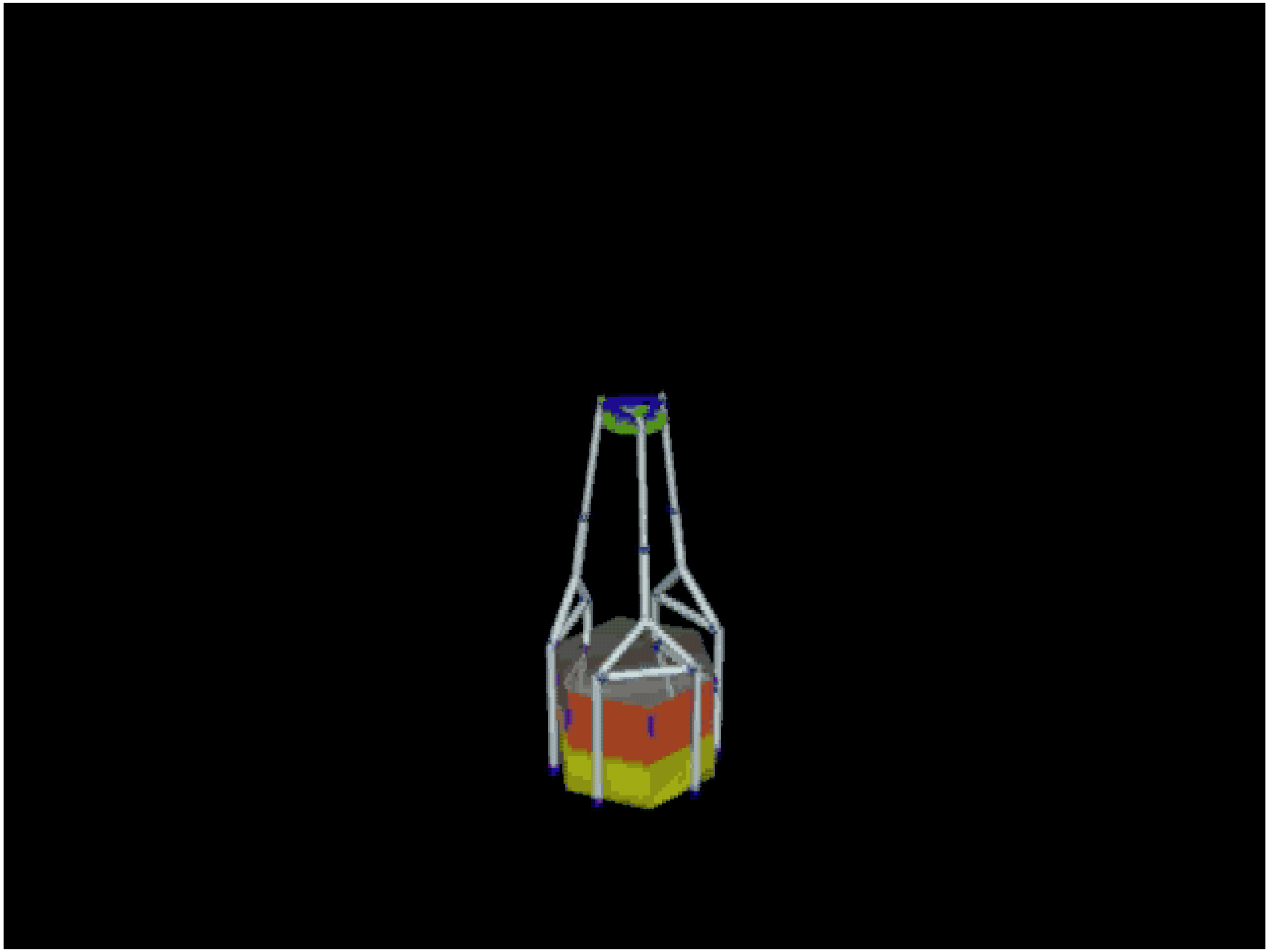


Testbed Configuration



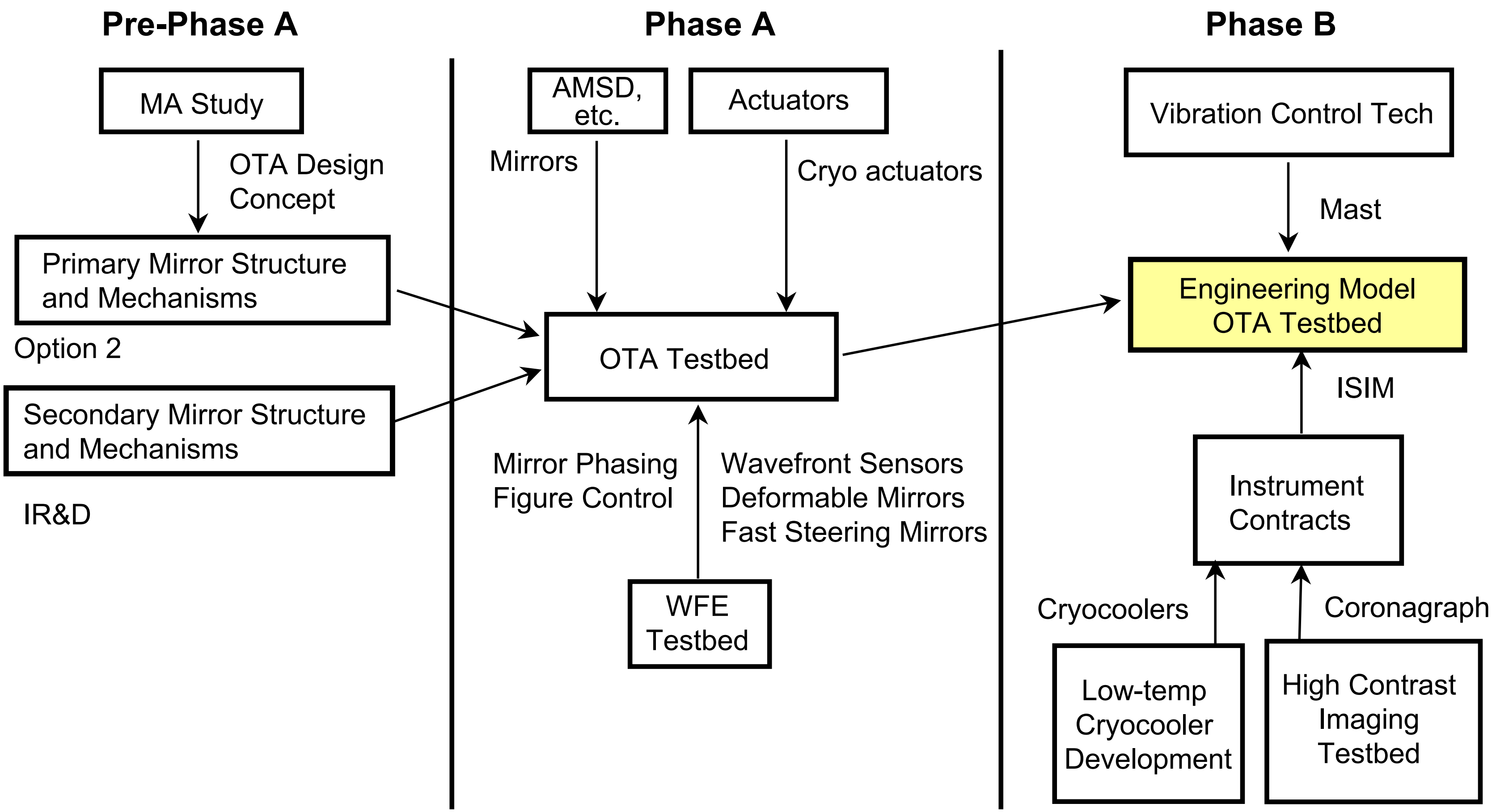
Telescope Deployment

TRW



Testbed Development Plan

TRW



Technology development effort culminates in Engineering Model Testbed

Technology Development Recommendations

TRW

- Optical Telescope Assembly (OTA)
  - Large, lightweight cryo-IR optics
  - Low cost mirror fabrication
  - Low temperature materials
  - Precision deployable structures
  - Deployable optics testbed
- Spacecraft
  - Active and passive vibration control with cryogenic damping
  - Lightweight deployable solar and thermal shields
  - High torque/high capacity momentum wheels

Technology Development Recommendations II

TRW

- Integrated Science Instrument Module (ISIM)
  - Low-vibration cryocoolers (4-6K)
  - Apodization technology for Lyot stops and occulting spots
  - Cryogenic opto-mechanics
  - Cryogenic deformable mirrors
  - Wavefront sensing and control
  - Low noise, large format SiAs detectors
  - Large IR filters and broadband transmissive substrates
  - Superconducting electronics
  - Low power, cryogenic electronics for FPA signal conditioning
  - Low power drivers for filter wheels and other mechanisms
  - High-contrast Imaging testbed

Coronagraph Technology Validation

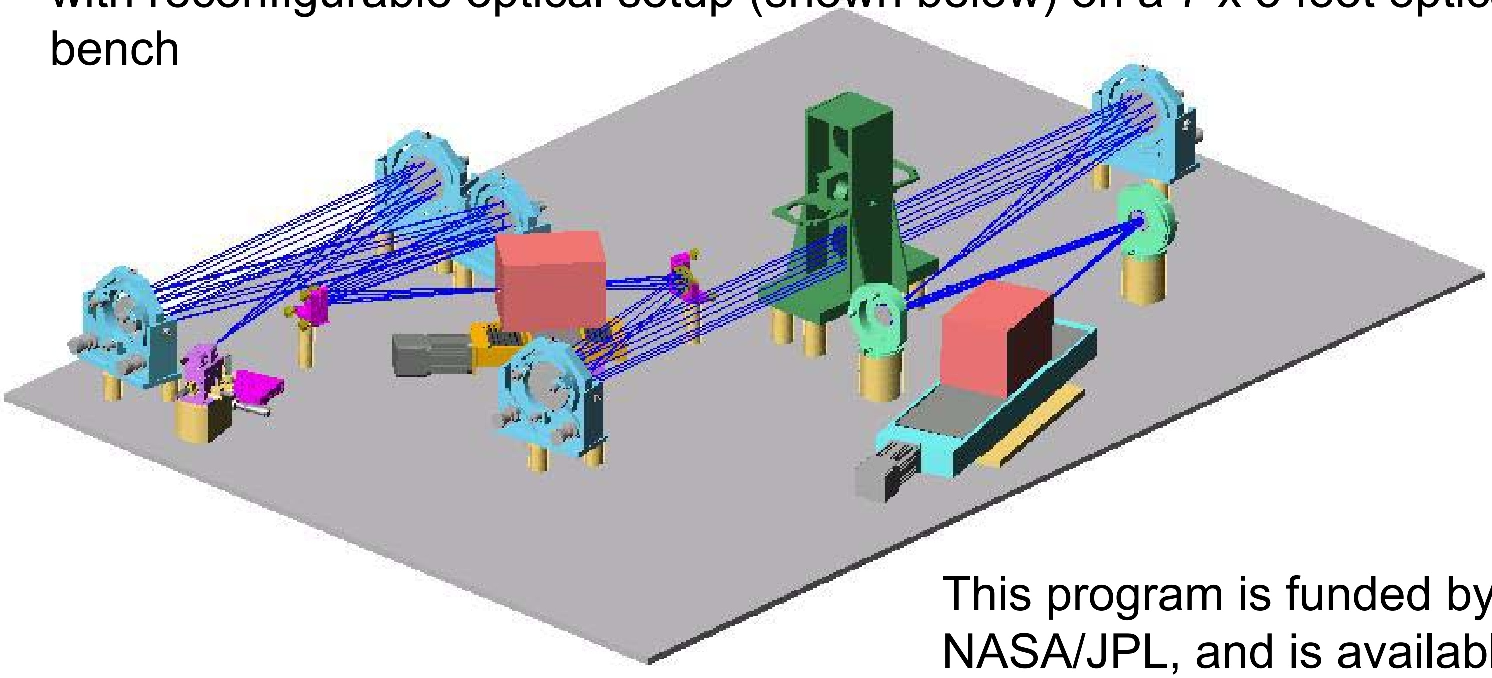
John Trauger

JPL

The Eclipse Testbed at JPL Provides Validation for Coronagraphy

TRW

- The goals of the "Eclipse Testbed" (ETB) is to validate key wavefront and scattered light control technologies to the accuracy required to achieve 109 contrast ratios or better in visible light
- Implemented as a vibration and temperature isolated vacuum testbed with reconfigurable optical setup (shown below) on a 7 x 5 foot optical bench



This program is funded by NASA/JPL, and is available to support the TPF program

ETB Has Key Goals to Validate TPF Coronagraph Technology Needs

TRW

- Scattered light reduction with active optical wavefront correction to 1 Angstrom rms or better with a high-order precision deformable mirror
  - 1400 actuator DM to be implemented in Spring 2002
  - 3200 actuator DM to be implemented by Fall 2002
- Diffracted light reduction with coronagraphic and apodizing techniques
  - Soft-edged coronagraph occulting spots
  - Range of hard- and soft-edged Lyot/pupil stops
- Precision wavefront sensing techniques available to a space telescope
  - Implemented using phase diversity algorithms with a CCD science camera moved through focus
  - Provides the information to set active wavefront correcting elements including the DM and any telescope alignment actuators
- High performance light baffling strategies
- Techniques used will validate our predictive models for a TPF coronagraph and possible precursor missions such as Eclipse

Precursor Missions to Validate Technology, Provide Science Data

TRW

- ETB will validate critical hardware and optical performance models for high contrast imaging in a space-like environment
- A precursor mission to validate the approach in a space environment would minimize risk for the TPF Coronagraph mission
  - Evaluate vibration isolation levels required to achieve desired image quality
  - Evaluate thermal control required
  - Evaluate methods of stray light control for a space based telescope
  - Validate scaling models from the testbed to a larger, operational system
  - Validate wave-front sensing and control algorithms in a space environment
- A precursor mission to do preliminary survey of target systems equally valuable
  - Determine exo-zodiacal dust/debris structures and densities to model integration time needed to defeat the zodiacal background
  - Detect presence of giant planets as signposts for stable planetary systems and safe harbors for terrestrial planets

Life Cycle Cost Estimate

C.Lillie/E.Wood

10-12 December 2001

Topics

- Ground Rules and Assumptions
- ROM Costs
- Funding Requirements

TPF Cost Ground Rules and Assumptions

TRW

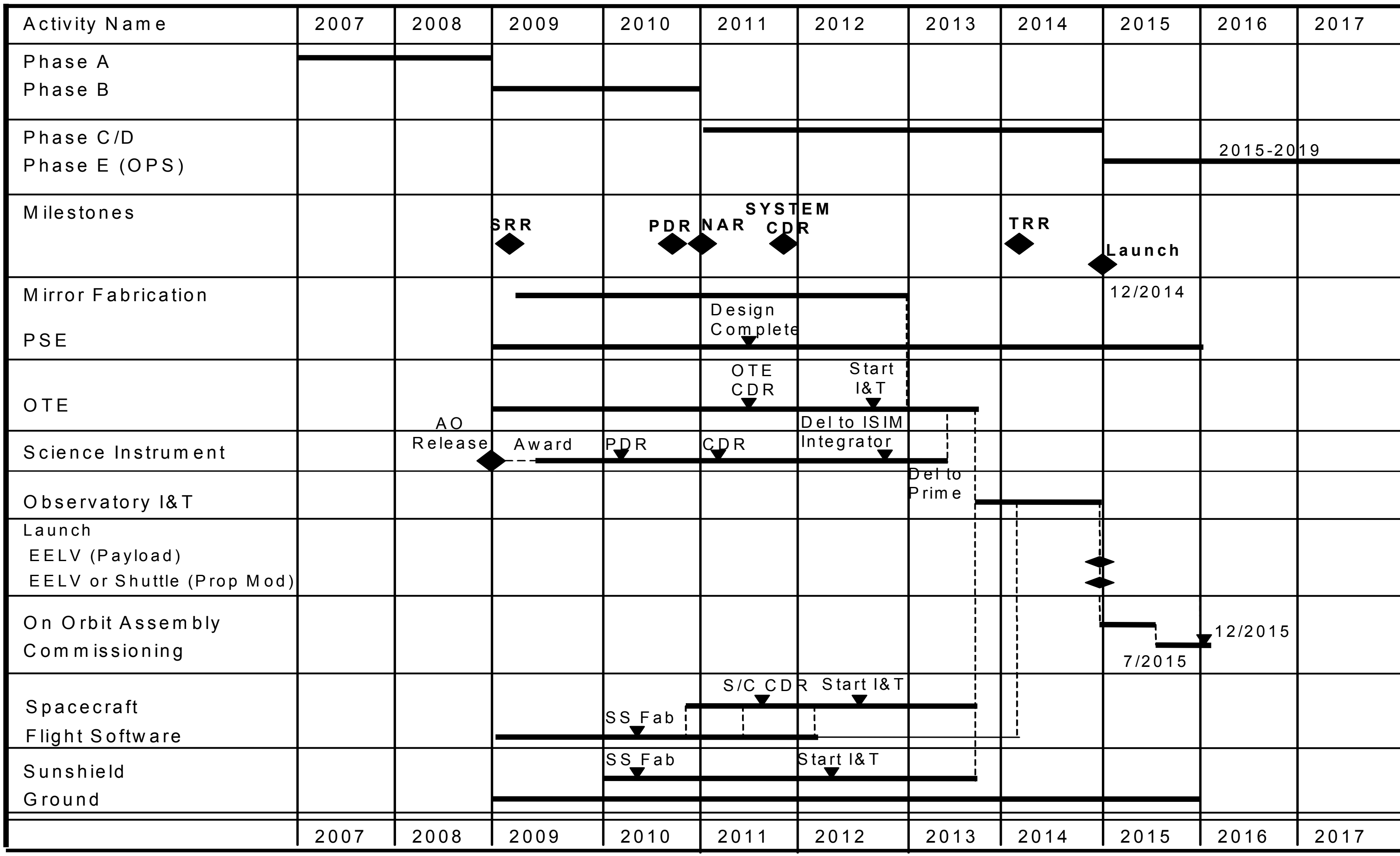
- Costs are in 2002 $M (including fee) with a reserve of 30%
  - Excludes science team and NASA center costs
  - No fee or reserve applied to launch vehicles
- Instrument delivery no later than last quarter 2012
- Launch in last quarter 2014 on a EELV Heavy
- Initial primary mirror and sunshield development begins in Phase A/B
- Cost estimates developed using a combination of cost analogies and statistically developed estimating relationships from our cost database
  - Estimate based on the WBS and TPF schedule developed for this study

TPF Work Breakdown Structure

- TPF
  - Program Mgmt 1.0
  - Systems Engrg 2.0
  - TPF Assembly, Integration and Test 3.0
    - Management/ Engineering
    - AI&T
      - Activities
      - Support Equip
      - Facilities
    - On-Orbit Assembly & Test
      - Delivery Shuttle/EELV
      - EVA Resources
      - ASE
  - Spacecraft 4.0
    - Management
    - I&T
    - Structures & Mechanisms
    - Power & Electrical
    - Thermal Management
    - Attitude Control Subsystem (ACS)
    - Propulsion
    - Communications
    - Engineering Data Interface
    - TPF Flight Software
  - Telescope 5.0
    - Management
    - I&T
    - Primary Mirror Assembly
    - Secondary Mirror Assembly
    - Post-Secondary Optics
    - Wavefront Sensing (WFS) & Correction
    - Integrating Structure
    - Power and Electrical
    - Thermal Management
    - Engineering Data Interface
  - Science Instruments 6.0
    - Management/ Engineering
    - I&T
    - Cronagraph
    - Fine Guidance Sensor
    - Imaging Instrument
  - Mission Ops and Data Analysis 7.0
    - Management/ Engineering
    - I&T
    - Ground Station & Infrastructure
    - Space-Ground Communications
    - Command & Data Handling (C&DH)
    - Data Proc., Storage/ Archive, Distribution
    - Operations

TPF Schedule

TRW



Total TPF Costs

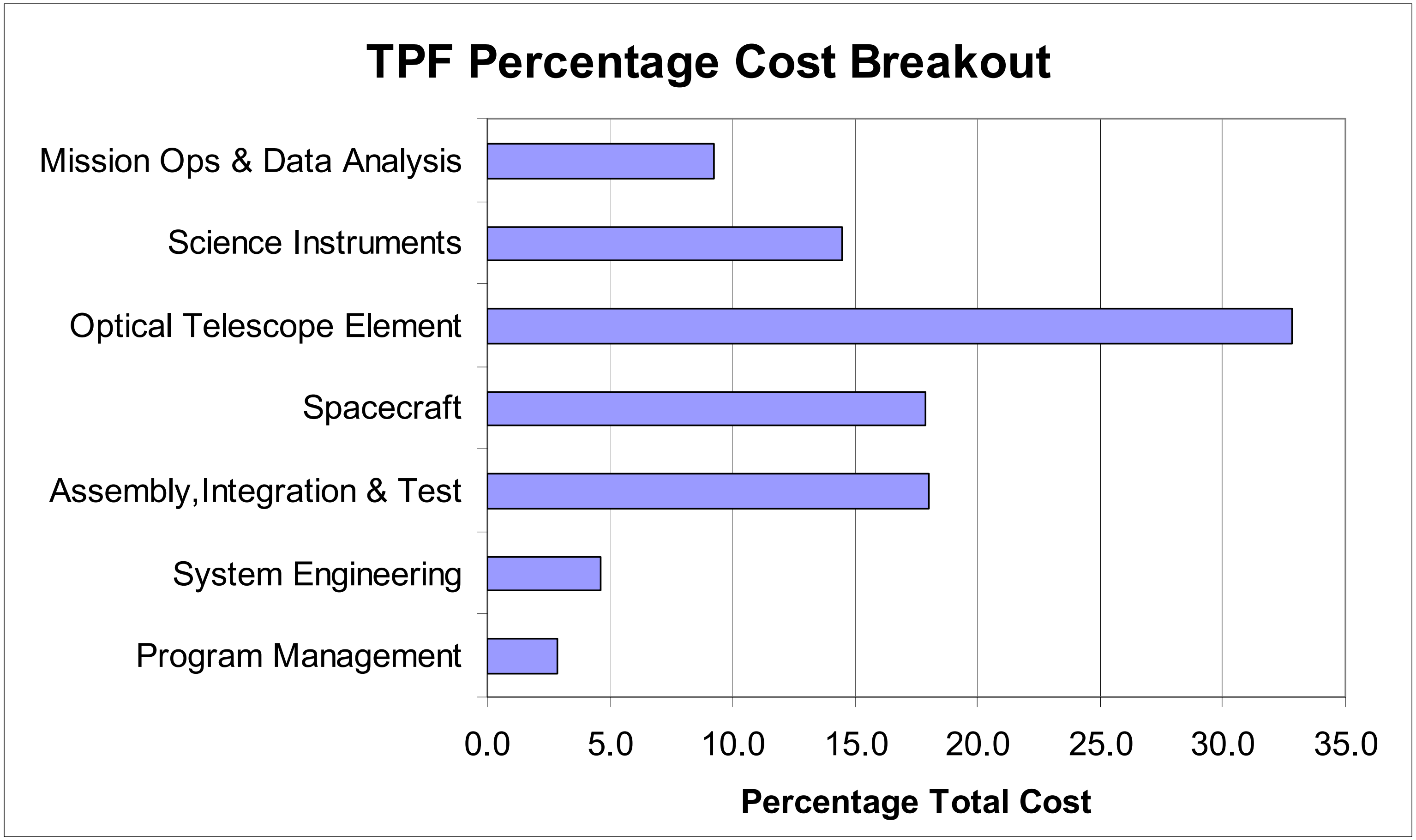
TRW

WBS	Description	Total 2002$M
	TPF Total	1896
1.0	Program Management	54
2.0	System Engineering	88
3.0	Assembly,Integration & Test	342
4.0	Spacecraft	339
5.0	Optical Telescope Element	623
6.0	Science Instruments	275
7.0	Mission Ops & Data Analysis	175

- TPF total costs exclude:
  - Annual science operations costs
  - Support from NASA centers
- Delta cost for on-orbit assembly and test operations (including shuttle) of 250 $M not included in TPF total

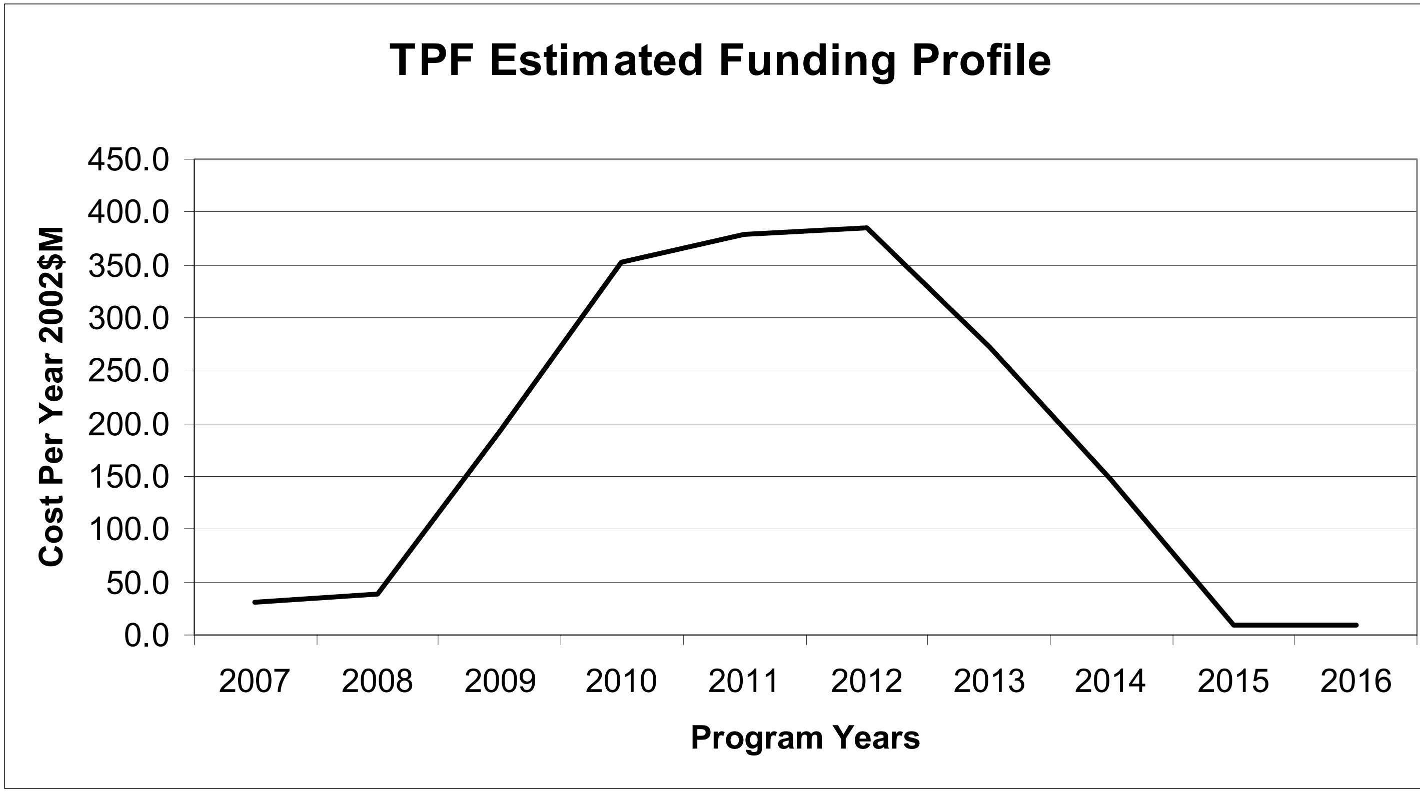
TPF Cost Breakout

TRW



TPF Funding Requirements

TRW



	2007	2008	2009	2010	2011	2012	2013	2014	2015
Total Cost/Year	31.5	39.3	193.3	352.2	379.4	384.9	272.4	146.9	8.6

Costs constant at 10$M/Year for years 2015 through 2024

Summary

Charles Lillie
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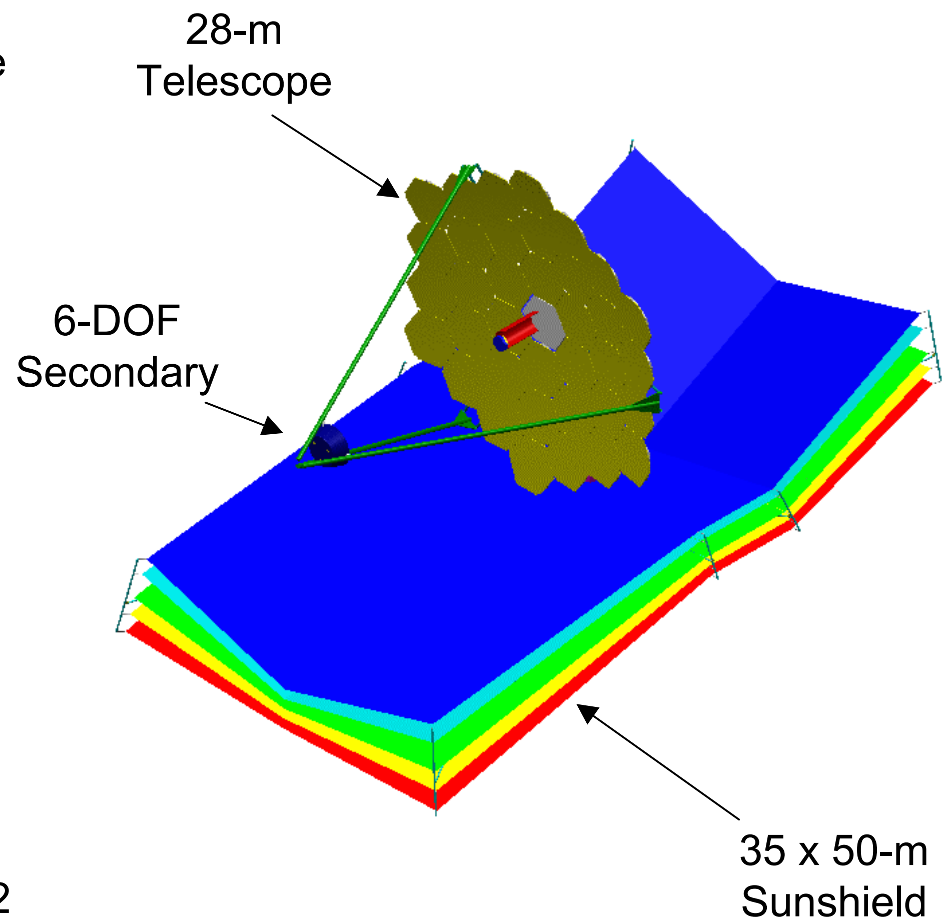
IR Coronagraph Design Concept

- 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
  - 107 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



Advantages of Direct Imaging and Coronagraphy

TRW

- Direct Imagers **have more science utility** than synthetic aperture imagers, since they:
  - Are less subject to confusion
  - Handle extended objects better
  - Readily support spectroscopy
  - Have the flexibility to respond to the unexpected
- Direct imaging **is less complex** to implement, and does not require:
  - Beam transport over long distances
  - Array rotation or chopping
  - Precision pathlength control
- Direct imaging and IR coronagraphy **requires less technology development**, thanks to:
  - Heritage from SIRTF, SIM and NGST
  - Coronagraph technology being developed at JPL with the Eclipse testbed
- Direct imagers **can be scaled directly to the LifeFinder and Planet Imager** missions

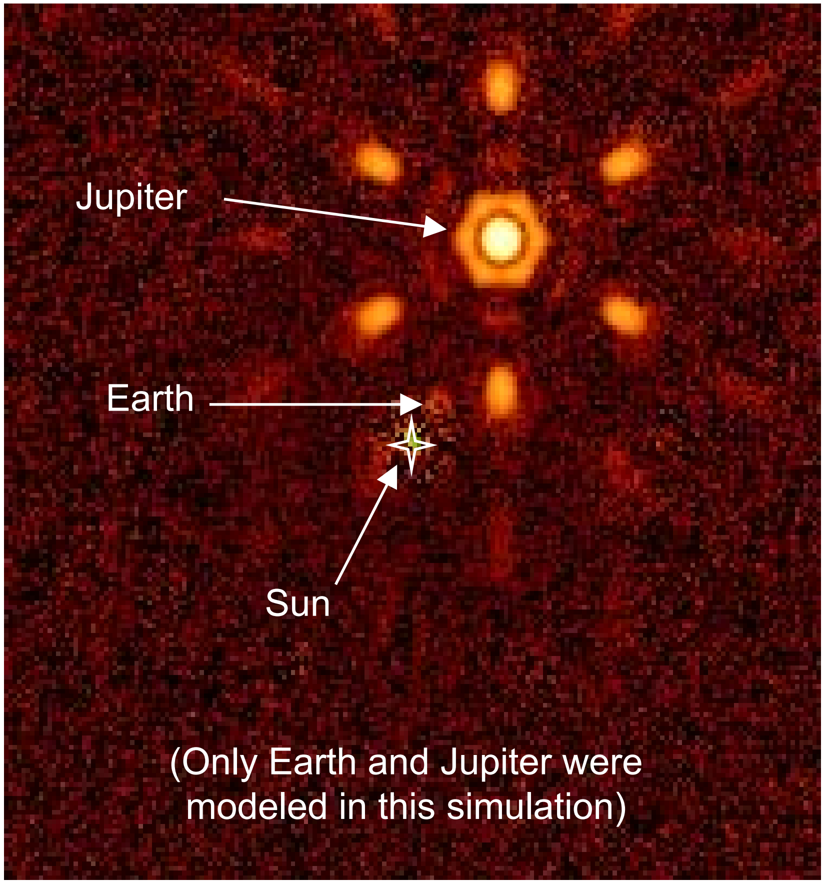
Feasibility Assessment

TRW

- Mission is technically feasible, provided enabling technologies are developed in the 2002-2009 period
  - No “breakthroughs” required
  - Extension of current state-of-the-art
  - Many missions enabled by TPF technology development
- TPF can be launched in late 2014 if recommended schedule is adopted
  - PDR in late-2010, CDR in late-2011
- Mission can be accomplished for LCC of ~$1,900M in FY02 dollars
  - Science team and NASA Center costs not included
- IR Coronagraph can achieve TPF mission objectives, and more
  - Powerful tool for imaging and spectroscopy of other astrophysical objects

A Powerful Tool for Planet Detection and Other Astrophysics

TRW



The Earth at 10pc is detected at S/N = 5 at 10 μ with a 2.4-hour integration

A three-color Hubble Deep Field image can be obtained in 5 minutes

TRW

Phase 2 Study Team

Industry

Name	Company/Role
Charlie Atkinson	TRW Optics, I&T
Suzi Casement	TRW Science Instrument
Sherry Erdman	TRW Secretary
Marty Flannery	TRW Optical Design
Paul Glenn	Bauer Performance Model
John Kinney	TRW Data System
Keith Kroening	TRW Spacecraft, MDI
Chuck Lillie	TRW Program Manager
Ray Manning	TRW Dynamics
Gary Matthews	Kodak Optics Support
Leo Matuszak	TRW Launch Vehicles
Stewart Moses	TRW System Engineer
Tammy Ortiz	TRW Contracts
Annette Palazuelos	TRW Business
John Pohner	TRW Thermal Analysis

Industry

Name	Company/Role
Bob Robitaille	TRW Pricing
Ken Sitarski	TRW Subcontracts
Maraia Tanner	TRW Mechanical Design
Frank Tung	TRW Attitude Control
Ed Wood	West Winds Cost Analysis

Science Team

Name	Organization
Alan Dressler	Carnegie-Mellon University
James Larkin	UCLA
Doug Lin	Lick Observatory
Richard Simon	NAAO
Glenn Starkman	Case Western Reserve Univ.
John Trauger	JPL
Dan Weedman	Self
Ned Wright	UCLA

TRW Team

TRW

Team Member	Role
• Science Team	Phenomenology, concepts, astrophysics, concept assessments
• TRW	Prime, system engineering, spacecraft
• Bauer	System performance modeling
• Kodak	Optical technology
• ITT	Modeling, instrument technology
• LLNL	Modeling, instrument technology
• SEE	Orbit analysis
• SDL	Instrument technology