

# Next Generation Space Telescope (NGST) Observatory Architecture and Performance

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## ABSTRACT

NGST will be used to help understand the shape and chemical composition of the universe, and the evolution of galaxies, stars and planets. With its 7 meter primary mirror the Observatory will observe red shifted light from the early history of the universe, and will be capable of seeing objects 400 times fainter than seen from large ground-based telescopes or the current generation of space-based infrared telescopes. NASA Goddard Space Flight Center (GSFC) manages NGST with contributions from a number of academic, government, and industrial partners. The contract to build the space based observatory for NGST has been awarded to the TRW/Ball/Kodak team.

**Keywords:** NGST, space-based, observatory, infrared

## 1. INTRODUCTION

NASA's Next Generation Space Telescope (NGST) will be the premier program for astrophysics in the decade following its launch. NGST will observe the early universe, at an age between 1 million and a few billion years, a period during which the first stars and galaxies began to form. NGST is an infrared observatory instrumented for imaging and spectroscopy, diffraction limited at 2 $\mu$ m, with approximately a 0.1 arcsec resolution, nano-Jansky sensitivity, and a large field of view.

This paper presents the architecture of the NGST Observatory, and describes its performance and design features. The observatory is composed of: an Optical Telescope Element (OTE), an Integrated Science Instrument Module (ISIM), a spacecraft, and a sunshield. The OTE is a deployable optical system with diffraction limited performance at 2  $\mu$ m and a stable point spread function (PSF). The OTE provides a low emission and scatter background to the ISIM. The ISIM consists of three science instruments (SIs): 1) a near-infrared (0.6 to 5  $\mu$ m) camera - NIRCam, 2) a near-infrared (0.6 to 5  $\mu$ m) multi-object spectrometer- NIRSpec, 3) a mid-infrared (5 to 30  $\mu$ m) camera- MIRI, and also includes a fine guidance sensor -FGS. The spacecraft provides a highly stable pointing platform and housekeeping functions for the observatory. The sunshield shades the OTE and ISIM from solar illumination to allow operation with high sensitivity past 20  $\mu$ m. This paper describe the OTE, spacecraft and sunshield portions of the observatory. Current specifications for the ISIM are used to predict observatory performance. Other papers in this conference discuss the ISIM instruments as well as details on specific portions of the NGST Observatory.

## 2. OBSERVATORY ARCHITECTURE

The NGST observatory (Figure 1) has three elements: Optical Telescope Element (OTE), Integrated Science Instrument Module (ISIM) Element, and Spacecraft Element (Spacecraft Bus and Sunshield). Our architecture meets the observatory requirements with margin, providing a high degree of confidence in achieving the NGST objectives. The observatory uses simple passive thermal control, uncomplicated and reliable deployments, robust wavefront control, and is testable in a 1-g environment. We incorporate mature technologies wherever possible, augmented with recent innovations funded by NASA to reduce development risks and to meet cost and schedule requirements. By carefully choosing our design configuration, we avoid complexity, resulting in a design that minimizes untestable aspects of performance, unnecessary active control systems, complex operational systems, and unusual ground test equipment. Our observatory is fairly insensitive to environmental variables both in space (e.g., absolute temperature of the primary, sun angle variations, and solar torque) and on the ground (e.g., gravity effects). This simplifies both orbital operations and ground testing.

## 2.1 Key features of NGST Observatory

Figure 2 summarizes key features of our architecture. A key aspect of our architecture is the use of semi-rigid primary mirror segments mounted on a very stable and rigid backplane composite structure. We refer to the architecture as “semi-rigid” because it has a modest amount of flexibility that allows for on-orbit compensation of segment-to-segment radius of curvature variations.

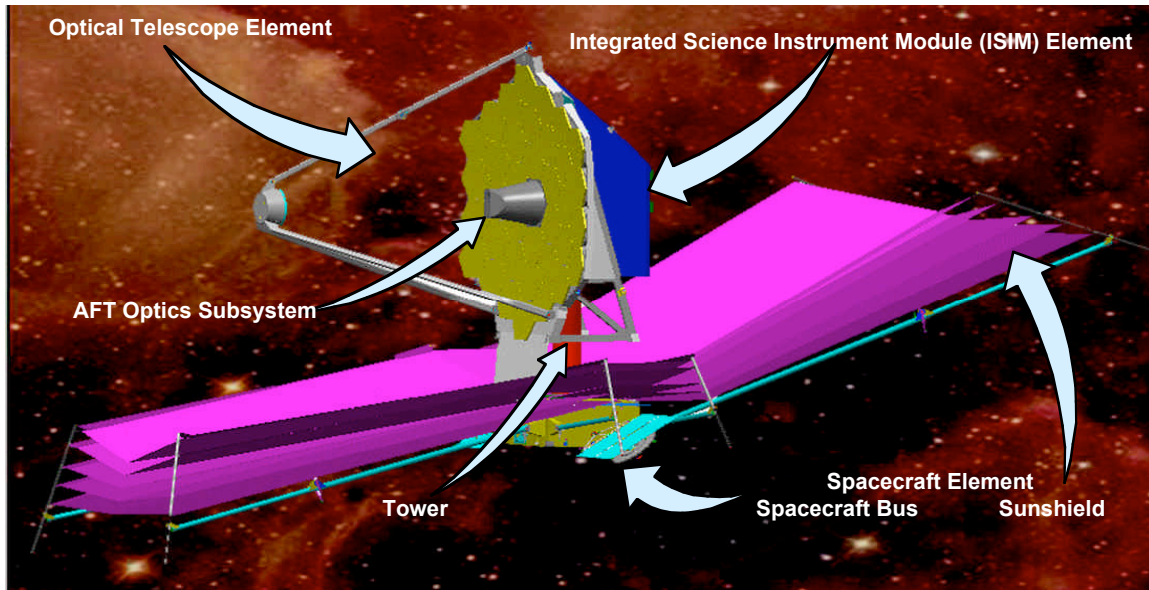


Figure 1. NGST Observatory

Semi-rigid segments have a high degree of inherent optical quality and stability, allowing us to verify optical performance by 1-g end-to-end ground testing before launch. The semi-rigid approach also supports high-confidence, predictable commissioning and optical figure maintenance, while reducing the number of actuators and electrical cables with their associated heat leaks. Each semi-rigid segment is fully tested on the ground to verify the proper optical figure at cryogenic temperature. Our wavefront control concept uses rigid body (tip-tilt-piston) adjustment of individual mirror segments to achieve a diffraction-limited large aperture telescope. The telescope wavefront control system is fully tested at cryogenic temperatures on the ground.

Our baseline implementation of the semi-rigid approach uses Beryllium (Be) mirrors. Beryllium mirrors are proven in past infrared applications in space, such as IRAS and COBE, and their material properties are known down to 10K. Further, Beryllium fabrication steps have been characterized using the government-funded Advanced Mirror System Demonstrator (AMSD) results. Our architecture can also allow use of either ultra low expansion (ULE) glass for the mirror material. With NASA/GSFC participation, test results from AMSD will be used to select the final mirror material to best balance cost, risk and schedule.

Another important aspect of our design is the sunshield. Because it passively maintains the OTE and ISIM at very stable cryogenic conditions, the sunshield allows us to take full advantage of the steady thermal conditions at the L2 orbit. Thermal stability is further enhanced by the two-chord fold architecture of the primary mirror. This folding architecture allows simple thermal straps across the hinge lines and results in a uniform temperature distribution on the primary mirror structure. With these features, the observatory can maintain its optical performance and optical stability for any pointing within its field-of-regard without relying on active thermal control or active wavefront control. The Sunshield deployment concept is based on TRW's precision antenna mesh system which we have used for many space deployments without a single deployment failure.

## 3 OBSERVATORY PREDICTED PERFORMANCE

Figure 3 summarizes our predicted performance for the NGST Observatory. The imaging performance of the telescope must be diffraction limited at  $2 \mu\text{m}$ ; its encircled energy (EE) at 150-milli arc seconds (mas) must exceed 75%, and the stability of the point spread function (PSF) must be better than 2%. Our evaluation of performance includes a 50% minimum margin on the calculated thermal loads, worst-case numbers for the measured coefficient of thermal expansion (CTE), and a Monte Carlo simulation of the distribution of wavefront errors.

Feature		Benefit
Optical Telescope Element	<ul style="list-style-type: none"> <li>• Three mirror anastigmat (TMA) design, f/16.7, 29.4 m<sup>2</sup> collecting area</li> <li>• Fine steering mirror (FSM) to provide line-of-sight (LOS) stabilization 6.6 mas</li> <li>• Four separate deployments</li> <li>• Semi-rigid hexagonal mirror segments and graphite composite backplane structure</li> </ul>	<ul style="list-style-type: none"> <li>• Superior image quality over the ISIM FOV, provides science resolution and sensitivity</li> <li>• Excellent pointing control and stability in conjunction with the spacecraft attitude control</li> <li>• Simple, reliable and robust deployment</li> <li>• Allows ground verification of the OTE, provides stable optical performance over temperature</li> </ul>
Primary Mirror	<ul style="list-style-type: none"> <li>• Primary mirror deploys in two steps (2-chord fold)</li> <li>• 2-chord fold allows for thermal strapping across hinge lines</li> <li>• Composed of 36 semi-rigid hexagonal segments, each with set-and-monitor wavefront control actuators</li> <li>• Baseline mirror segment material is Beryllium</li> </ul>	<ul style="list-style-type: none"> <li>• Highly reliable deployment</li> <li>• Provides radial and azimuthal thermal conductivity for reducing thermal gradients; provides longer mission observation time.</li> <li>• All segments are mechanically identical, achieving efficiencies in manufacturing, assembly and testing</li> <li>• Known material properties with demonstrated optical performance over temperature</li> </ul>
Secondary Mirror	<ul style="list-style-type: none"> <li>• Tripod configuration for support structure</li> <li>• Deployment using a single redundant actuator</li> <li>• Semi-rigid optic with 6 degrees of freedom (DOF) alignment</li> </ul>	<ul style="list-style-type: none"> <li>• Provides rigidity, minimizes obscuration and scattered light into the field of view</li> <li>• Low risk, high margin (torque margin &gt;32 times the friction load)</li> <li>• Permits reliable and accurate telescope alignment</li> </ul>
Aft Optics	<ul style="list-style-type: none"> <li>• Fixed baffle</li> </ul>	<ul style="list-style-type: none"> <li>• Reduces stray light and houses the tertiary mirror and the FSM</li> </ul>
ISIM	<ul style="list-style-type: none"> <li>• Simple 3-point kinematic mount; 9 m<sup>2</sup> of thermal radiators, and 23 m<sup>3</sup> volume.</li> <li>• Large IFOV OTE</li> </ul>	<ul style="list-style-type: none"> <li>• Provides a simple interface for the ISIM to decouple ISIM development from the OTE.</li> <li>• Simultaneous operation of SIs and FGS</li> </ul>
Tower	<ul style="list-style-type: none"> <li>• Integral 1 Hz passive vibration isolators</li> <li>• Thermally isolates the OTE from spacecraft</li> </ul>	<ul style="list-style-type: none"> <li>• Reduces spacecraft dynamic noise in the OTE</li> <li>• Achieves small mirror temperature gradients</li> </ul>
Sunshield	<ul style="list-style-type: none"> <li>• 5 layer "V" groove radiator design reduces solar energy to 23 mwatts</li> <li>• Folded about OTE during launch</li> <li>• Sized (~22 m x 10 m) and shaped to meet or exceed field-of-regard requirements</li> </ul>	<ul style="list-style-type: none"> <li>• Provides a stable thermal environment for passively cooling the OTE and the ISIM</li> <li>• Reliable deployment, protects OTE during launch</li> <li>• Reduces the time and fuel for momentum unloading, Increases operational efficiency</li> </ul>
Spacecraft Bus	<ul style="list-style-type: none"> <li>• Chandra-based attitude control subsystem</li> <li>• Two-axis gimballed high gain earth-pointing antenna with omnis, X &amp; S band</li> <li>• 232 Gbit solid state recorder</li> <li>• Propellant for &gt;12 years</li> </ul>	<ul style="list-style-type: none"> <li>• Flight-proven low noise dynamic environment that minimizes line-of-sight jitter</li> <li>• Contingency operations and link margin</li> <li>• Store &gt; 2 days of science &amp; engineering data</li> <li>• Extended operation capability</li> </ul>

Figure 2. Observatory Key Features and Benefits

We estimate over 500 kg of management reserve against the 5400 kg weight limit. This reserve is over and above mass contingencies. We expect contingencies will be used as the design matures. All deployments have been analyzed for reliability using fault trees and probabilistic risk assessments. Some cases included torque margins upwards of 32 times the estimated friction load to assure reliable deployment. The field-of-regard (FOR) for the observatory significantly exceeds requirements. Such an FOR allows extensive operational flexibility for scheduling science observations, and provides alternatives for station keeping as a contingency operation. In the FOR performance, a 5 degree angular safety margin has been maintained for over and above the values quoted.

### 3.1 Design reference mission

Science needs for the NGST observatory are defined by a baseline set of astronomical observations called the Design Reference Mission (DRM). The time required to complete the DRM must be less than 5 years, with a goal of 2.5 years. Our NGST architecture completes the DRM in approximately 2.55 years, providing an increase in science value for the mission. This prediction is based on our architecture, using version 2.3 of the DRM and the NGST Mission Simulator (NMS) release 2.9a.

Parameter	Requirement	Capability
<b>Schedule</b>	Launch readiness: June 2010	Consistent with technology & schedule
<b>Wavelength</b>	0.6 to >10 $\mu\text{m}$	0.6 to >30 $\mu\text{m}$ . Reflective gold coatings
<b>Sensitivity</b>	Targets at the North Ecliptic Pole and with a 100,000 s integration, the minimum sensitivities (see below) shall be met with an SNR of 10. 1.3 nJy at 0.7 $\mu\text{m}$ and R = 5 1.6 nJy at 2.0 $\mu\text{m}$ and R = 5 160 nJy at 2.0 $\mu\text{m}$ and R = 1000 73 nJy at 10 $\mu\text{m}$ and R = 3 3,600 nJy at 10 $\mu\text{m}$ and R = 1,500 800 nJy at 20 $\mu\text{m}$ and R = 3 18,000 nJy at 20 $\mu\text{m}$ and R = 1500	SNR margins varying from 20-59%. 29.4 m <sup>2</sup> collecting area with flat-to-flat dimension of 7 m. 0.90 nJy at 0.7 $\mu\text{m}$ and R = 5 1.12 nJy at 2 $\mu\text{m}$ and R = 5 93 nJy at 2 $\mu\text{m}$ and R = 1000 50 nJy at 10 $\mu\text{m}$ and R = 3 2,540 nJy at 10 $\mu\text{m}$ and R = 1500 274 nJy at 20 $\mu\text{m}$ and R = 3 7,140 nJy at 20 $\mu\text{m}$ and R = 1500
<b>Spatial Resolution &amp; Stability</b>	Total encircled energy (EE greater than 75% at 0.15 arcsecond radius at a wavelength of 1 $\mu\text{m}$ Strehl ratio at 2 $\mu\text{m}$ greater than or equal to 0.8 Less than 2% RMS variation about the mean over a 24-hour period over FOR	EE of 82% at 1 $\mu\text{m}$ and 150mas radius Strehl ratio of 0.84 at 2 $\mu\text{m}$ . Maximum peak to peak variation less than 0.2% over extended FOR
<b>Telescope FOV</b>	Spatially Separated FOVs 0.6 – 5 $\mu\text{m}$ $\geq$ 21 sq arcminutes 1 – 5 $\mu\text{m}$ $\geq$ 12 sq arcminutes >5 $\mu\text{m}$ , Imaging $\geq$ 5.2 sq arcminutes >5 $\mu\text{m}$ , Spectroscopy N/A	> 105 square arcminutes FOV. Capability of increasing field stop for a larger FOV; FOV locations and formats to be coordinated with final Science Instrument suppliers
<b>Celestial Sphere Coverage</b>	Over an interval of one sidereal year, capable of observing anywhere within the celestial sphere, with at least 35% available at any given time 50% of the celestial sphere must have continuous visibility for at least 60 days per year	100% annually 48.9% at any given time 100% of sphere has at least 69 contiguous days visibility 55% for > 196 days
<b>Mission Life</b>	Lifetime after commissioning 5-year minimum: 10-year goal Consumables sized for 10 years Time from launch to completion of commissioning shall not exceed 6 months	5-year minimum lifetime and no life limited item except for fuel 10 years for consumables Commissioning in less than approximately 4 months
<b>Orbit</b>	NGST shall orbit about L2 point	Halo orbit about L2
<b>Overall Observing Efficiency</b>	Goal >70% (science exposure time to total time)	Observatory ~ 77.2% OTE/Spacecraft efficiency ~92%. ISIM allocation: 85%
<b>Launch &amp; Mass</b>	5 m fairing, 5400 kg payload mass maximum	509 kg management reserve over and above contingency/margin

Figure 3. Performance of NGST Observatory for Key Driving Requirements

### 3.2 Encircled energy and PSF stability

**Encircled energy (EE)**- The EE requirement is used to determine the allowed optical wavefront error (WFE) and represents the imaging performance of NGST. The stability requirement is needed to reliably deconvolve the optical PSFs from different targets or for the same target at different observations. Figure 4 gives our estimate for the NGST encircled energy performance. Our expected performance is 82% versus the >75% requirement at 150 mas. The plot shows an encircled energy for a “perfect optic,” one composed of perfect hexagonal segments with gaps and obscurations. A Monte Carlo analysis was performed for our 7-m design by varying the spatial characteristics of the errors. Our estimated wavefront error is 112 nm rms (125 nm is allocated) and our estimated image motion (LOS jitter) is 6.6 mas (7.4 mas is allocated). The Strehl ratio at  $\lambda = 2\mu\text{m}$  is 0.84, well above the 0.8 criterion. The WFE used in this prediction includes ISIM contributions as well as those from the OTE.

**PSF stability-** A second important requirement is that the above mean encircled energy must vary by less than 2% for any combination of pointing within the required FOV over a 24-hour period. This requirement limits the allowed thermal-induced variations in the WFE over different pointing conditions within the observatory FOR. Detailed models are used to predict the worst-case temperature change and gradients. The results are combined with entries of the optical WFE budget to calculate the stability of the telescope PSF. EE stability has been evaluated for the worst-case (hot-to-cold) thermal slew. Our system is very stable, having less than 28 nm rms change in the WFE. The variability of the encircled energy at  $\sigma = 1 \mu\text{m}$  is less than 0.5% at the 150 mas radius, providing significant margin against the requirement to be less than 2% rms variation about the mean. The outstanding passive stability of the observatory PSF over the FOR allows the OTE to be repointed and immediately available for science observations. There is no need to wait for thermal settling (which reduces observational efficiency). Nor are wavefront corrections (which reduce observational efficiency) required. There is no need to provide heat inputs to adjust the temperature OTE profile (which reduce operational efficiency). Our design provides a thermally robust backplane (M55J/Boron composite) that has a low and stable CTE below 90K – little thermal deformation occurs over the FOR. The sunshield participates in this robust design by reducing the FOR-dependent heat load variations to a low level.

### 3.3 Sky coverage and continuous visibility

Field of regard refers to the fraction of the celestial sphere that the telescope may point towards at any given time. A large FOR is beneficial in terms of number of days per year of target visibility, ability to visit targets repeatedly for time variability studies, and flexibility to schedule observations, to revisit failed observations, and to respond to targets of opportunity. Our field of regard is limited by the size of the sunshield, which keeps the telescope in the shade.

Sky coverage performance is shown in Figure 5. A continuous viewing zone within 5° of

both the north and south ecliptic poles is available throughout the year. Fifty-five percent of the sky can be viewed continuously for at least 194 continuous days. This provides significantly greater operation utility than the requirement of >50% for 60 continuous days. All regions of the sky have at least 69 days of continuous visibility per year. Our architecture provides a FOR at any epoch of approximately 49% (Figure 6.) This FOR extends 5° past the ecliptic pole, and provides 100% accessibility of the sky during a year period.

### 3.4 Sensitivity and straylight limitations

Many NGST observations will be background limited. The background is a combination of in-field zodiacal light, scattered thermal emission from the sunshield and telescope, scattered starlight, and scattered zodiacal light.

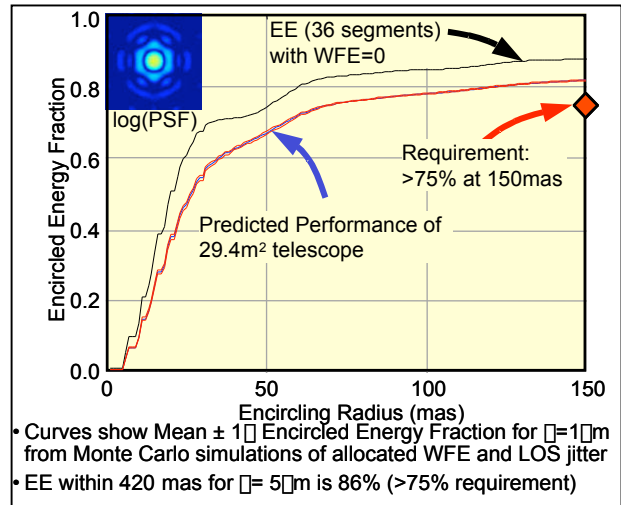


Figure 4 Predicted Encircled Energy

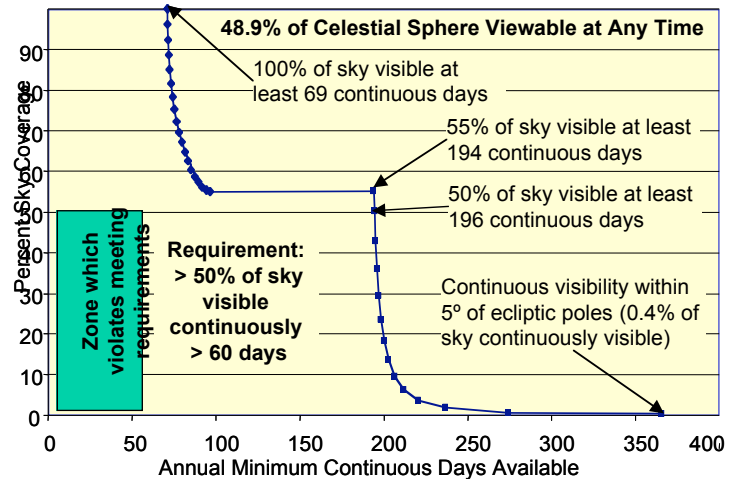


Figure 5. Sky Coverage of the NGST Observatory

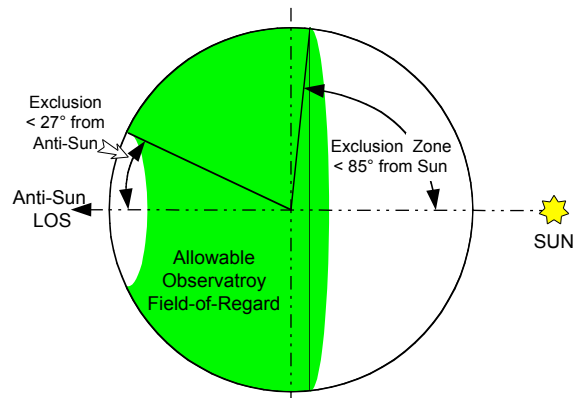


Figure 6. Observatory Field-of-Regard

Performance requirements for point source targets are defined at the ecliptic poles by the signal-to-noise ratio required for targets of certain brightness. Figure 7 gives the wavelength dependence of the Observatory sensitivity and the maximum effective background radiance for our architecture (identified as the sum of all individual thermal emissions).

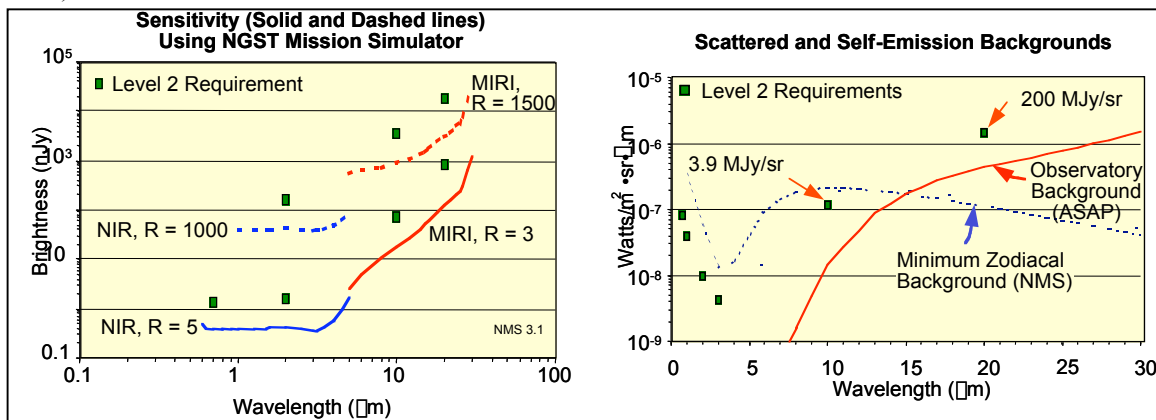


Figure 7 NGST Observatory Sensitivity and Equivalent Background

### 3.5 Observational efficiency

Observational efficiency limits the scientific productivity of the mission. Efficiency is the fraction of the total mission time spent actually “counting photons”, rather than occupied by activities such as slewing, stabilizing, calibrating, and adjusting parts of the Observatory. The Observatory is designed to be stable and simple to operate to minimize the time dedicated to activities other than obtaining science data. We predict an approximate 77% observational efficiency (Figure 8), providing significant margin against the >70% requirement. This achievement is in large part due to the significant advantages of the thermal design, isolation design, sunshield design, and wavefront sensing and control architecture.

Event / Task	Activity Duration over 5 year life
Slew, guide star acquisition, and settling	76 days
Small angle slews	14 days
Wavefront sensing and control	30 days
Momentum control	2 days
Stationkeeping	2 days
Thermal settling	0
Safe Mode	18 days
High Gain Antenna steering	0
Image quality monitoring	0
Sunshield reconfiguration	0
<b>Predicted OTE/Spacecraft Overhead</b>	142 days (7.8 %)
<b>ISIM Overhead Allocation</b>	274 days (15 %)
<b>Observatory Efficiency</b>	77.2%

Figure 8. Observational Efficiency Summary

The architecture provides significant thermal advantages, one of which is maintaining the optical performance after slewing from a hot thermal scenario to a cold thermal scenario. The design does not require any thermal settling time that would reduce observational efficiency. Included in the observational efficiency is an estimate for safe mode based on our design for the Chandra Observatory. The largest observatory contributors to observational inefficiency are the slew and the dither tasks. This indicates that our architecture is optimized in the sense that the overheads associated with pointing to targets are the dominant contributors to inefficiency.

## 4. OBSERVATORY DESIGN DESCRIPTION

### 4.1 Orbit

The observatory orbits about the second Lagrange (L2) point in the sun-earth system. We selected a large Halo orbit (shown in the view from the ecliptic pole in Figure 9.) that lies in a plane out of, but inclined slightly with respect to, the ecliptic plane. This orbit avoids earth and moon eclipses of the sun. Our architectural selection of a chord-fold primary with stable, low-CTE backplane material and excellent performance of the sunshield enable use of a stable

We plan to deploy the observatory and accomplish approximately 75 days of pre-commissioning, calibration, and operational training activities before achieving orbit at L2. Minimal time will be required to formally commission NGST at L2. Our semi-rigid mirror segment design allows for greater than 1 month intervals before a wavefront control adjustment is needed — 30 days total overhead over 5 years. Wavefront quality is monitored by using the science target imagery and therefore does not infringe on any observational time. Time intervals for momentum control are minimized by our sunshield design, which balances the induced observatory torque over the entire Field of Regard.

and passive thermal control rather than active thermal control for the OTE at the L2 orbit. The halo orbit period is approximately 6 months. Nominal station-keeping maneuvers are performed every half orbit (3 months). Cumulative station-keeping time (including orientation maneuvers) is less than 0.15% of the on-orbit time. Fuel for 12.6 years of operation at L2 is included.

Our Observatory readily fits into a Medium EELV launch vehicle with a 5-m fairing (Figure 9). The first stowed view (left) shows the sunshield stowed about the folded OTE. The second view (90° rotation) shown right eliminates the sunshield making evident the clearance between the fairing and the Observatory structural components is evident. Because the secondary faces down during launch, it is also shielded from particulate redistribution during launch. This configuration with the stowed sunshield protecting the folded telescope reduces contamination to the levels needed to meet sensitivity and stray light requirements.

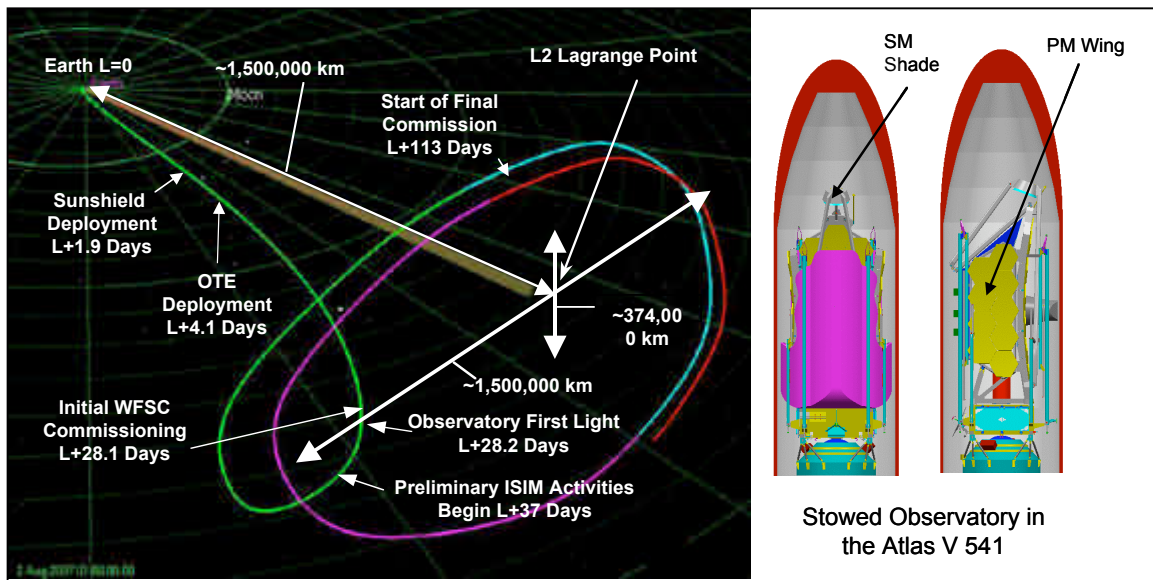


Figure 9. NGST Orbit /Trajectory to L2, and Stowed view in Atlas V

#### 4.2 Commissioning

Significant pre-commissioning activities occur during the transfer to L2. At 37 days after launch (see prior Figure 9), the observatory is available for ISIM pre-commissioning activities. Almost continuous ISIM availability for preliminary science observations is provided from this time until 106 days after launch, when a final TCM burn is required for injection into the L2 orbit. The intrinsic passive thermal stability of the semi-rigid mirror segment and the two-chord-fold primary allows early operation of science instruments. These pre-commissioning activities will develop an operational experience database so that formal commissioning and science operations may be conducted efficiently.

After the L2 orbit is achieved, a final checkout of all systems is initiated. Commissioning, complete 6 months after launch, includes ISIM, OTE, sunshield, and spacecraft performance verification operations that were not feasible during the transfer to L2. It also repeats selected operations performed during the transfer. The repeated operations ensure adequate knowledge of system performance in the final orbital-thermal conditions and allow comparisons with previous measurements. Examples of repeated operations include final distortion mappings for the observatory and the characterization of the Wavefront Sensing and Control (WFS&C) actuators' transfer function. Alloting 76 days for ISIM pre-commissioning activities allows us to both rehearse operations and increase familiarity with the observatory operations without reducing operational availability.

#### 4.3 Deployment

The observatory has the following five deployments; each is designed for simplicity, reliability, and accuracy: 1) deploy spacecraft bus appendages; 2) deploy sunshield, 3) extend tower (deployment), 4) deploy secondary mirror support structure, and 5) deploy primary mirror. Our design includes heaters and other protections that eliminate the need for time critical events and allow for unlatching and re-latching to relieve any residual long term stress in the structure. The secondary mirror deployment and primary mirror deployment sequence are shown in Figure 10.

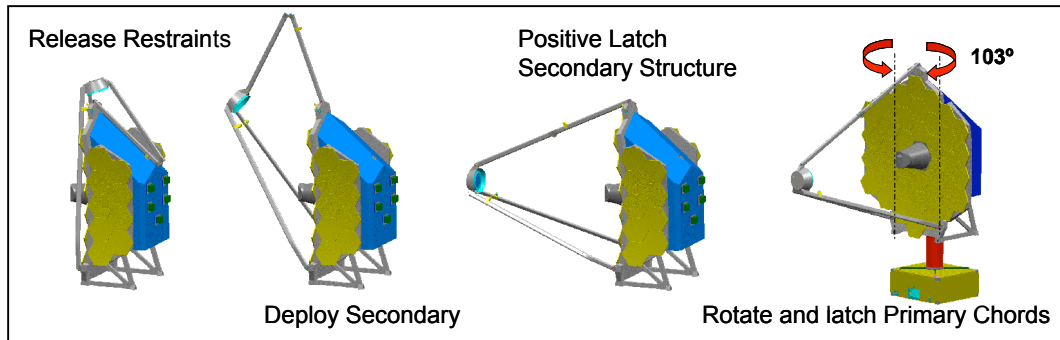


Figure 10. Telescope Deployment Sequence (Deployment steps 4 and 5)

#### 4.4 Optical Telescope Element

Our team’s design philosophy for the NGST OTE is to provide a well-corrected image to the ISIM using the simplest and most robust method. This philosophy led directly to: minimizing the number of mechanisms (especially those necessary to place the OTE into an operating configuration); designing the composite structure so that passive figure control and passive disturbance attenuation is possible; and designing a mirror segment with the minimum number of actuators to control the figure. Figure 11 shows the prescriptions for the NGST optical telescope.

Telescope Mirror Element	Position relative to Primary Vertex	Radius of Curvature	Aspheric Constant	Aperture Size (cm)
Primary		1,600 cm	$K = -0.995737$	700 flat-to-flat
Secondary	718.79 cm	189.57 cm	$K = -1.716789$	81.4
Secondary Focus	151.55 cm			
Tertiary	-93.98 cm	332.09 cm	$K = -0.624719$	63.5 x 44.7 decentered 24.9
Fine Steering Mirror	110.0 cm	Infinite		20
Focal Surface Interface to ISIM	-197.98 cm	309.42 cm		44.4 x 15.9

Figure 11. Optical Prescription of the NGST Telescope

The optical telescope is a 29.4 m<sup>2</sup> collecting area, three-mirror anastigmatic (TMA). It has an angular resolution of 71 mas at  $\lambda = 2 \mu\text{m}$  and allows for nano-Jansky sensitivity. The TMA configuration provides excellent image quality over a large field of view (FOV), accommodates all science instruments and the FGS, and facilitates efficient astronomical surveys. The optical prescriptions are well within manufacture and test capability for several optical vendors for both Beryllium and ULE. The prescriptions are used for tolerancing the telescope sensitivity for alignment requirements as well as predicting performance at temperature. The telescope has an effective f/number of 16.67. The effective focal length of 116.6 meters allows for critical sampling of the optical PSF at  $2 \mu\text{m}$  by the ISIM focal plane. An FSM is used for accurate optical pointing and image stabilization. The FSM is located at the image of the pupil, after the tertiary mirror but forward of the focal plane interface to the ISIM. The FSM, coupled with the low structural noise spacecraft, suppresses line-of-sight jitter to allow diffraction-limited performance at  $2 \mu\text{m}$ .

Figure 12 shows an isometric drawing of the telescope structure. The primary mirror is contained within a nominal 7.024-m diameter circle. The secondary mirror is supported by a deployable tripod support structure. This structure provides the necessary jitter stability with minimum complexity and beam blockage.

The design residual wavefront error (WFE) is shown in Figure 13, and is approximately 20 nm over the FOV. The OTE design is optimized to equalize performance over the

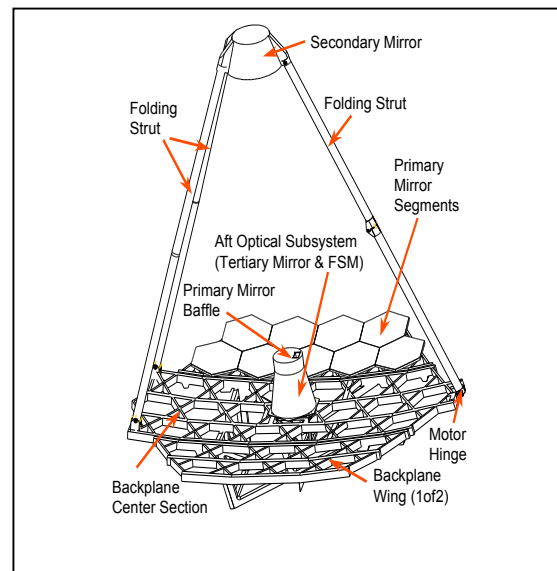


Figure 12. NGST Telescope Isometric View

total FOV. Significant tolerance is allocated to manufacturing and on-orbit environmental degradation since the design residual WFE is a very small contributor to the total system WFE allocation of 125 nm.

The NIRCcam focal plane arrays can be placed in a spatial region that has the lowest residual WFE to take full advantage of imaging performance. The mid-infrared instrument and NIR spectrometer can be positioned in an area with slightly larger WFE, but still well within the requirements for the instrument's performance. Similar considerations exist for placement of the FGS focal plane(s) within the telescope FOV. A re-optimization of the telescope performance over the FOV may be needed when the number and format for the NIRCcam and FGS focal planes are determined. Our design has great flexibility for packaging to accommodate instrument FOV needs. Telescope mirrors are coated with Gold (Au), with a broad spectral bandpass, from 0.6–30  $\mu\text{m}$ .

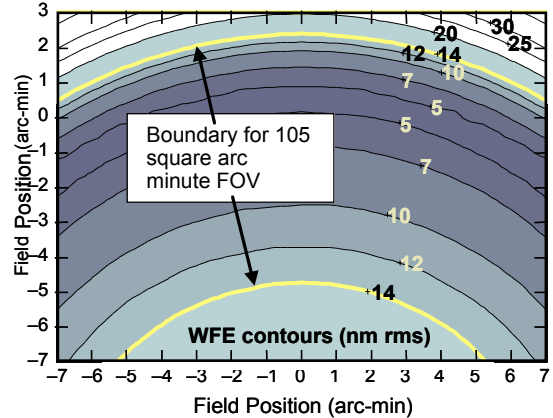


Figure 13 Telescope Design Residual Wavefront

#### 4.5 Mirror segments

The primary mirror is composed of 36 individual Be mirror segments (Figure 14). When properly phased relative to each other, these segments act as a single mirror. Primary mirror phasing is achieved via simple rigid body tip/tilt and piston of the individual segments. Each mirror segment is hexagonal with a 1 m flat-to-flat dimension. The 36 segments have six separate segment types with slightly different aspheric prescriptions depending on their placement. The six prescriptions are identified in Figure 14 by letters A, B, C, D, E, and F. Numbers 1 through 6 represent the six-fold symmetry of the hexagonal packing of the primary mirror. All segments within a type (letter) are completely interchangeable. The chord fold hinge lines are identified in the Figure. Using a 1-meter nominal primary mirror segment size allows the optical quality mid and high spatial frequency errors to be within the segment control and thereby its performance verified at the manufacture stage. The low frequency errors are corrected by the primary mirror adjustments on-orbit. The individual segments assume the performance capability that is being demonstrated on the AMSD program.

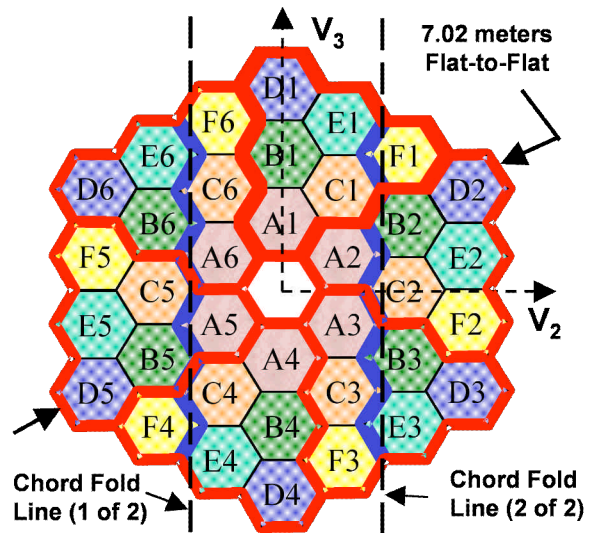


Figure 14. Definition of the Six Different Primary Mirror Segment Optical Prescriptions

As shown in Figure 15, four actuators are attached to the mirror. The architecture is “semi-rigid” because it has a modest amount of flexibility that allows for on-orbit compensation of segment-to-segment radius of curvature (ROC) variations. This ROC adjustment is made independent of any attachment to the backplane structure to prevent mirror distortion. The advantages of the semi-rigid segment are very low mirror figure changes due to 1-g effects, thereby supporting high-fidelity ground testing and a minimum number of actuators for each segment. Fewer actuators result in reduced mass, reduced complexity for wavefront control, and minimal support electronics.

The three outer actuators control each segment in piston, tip, and tilt. Each actuator is attached to a load spreader that distributes the interface load to two areas on the isogrid structure of the mirror segment (Figure 15). The three outer actuators mount the primary mirror segments directly to the primary mirror backplane without any intermediate reaction structure. A local strongback for supporting a fourth actuator at the center of the segment is attached to each interface location between the outer actuators and their corresponding load spreader. The fourth actuator controls the segment's radius of curvature and is independent of the rigid body actuators. A tripod load spreader distributes the interface loads at the center among three areas on the isogrid structure of the mirror segment. This separability between rigid body motion and radius of curvature corrections greatly simplifies the wavefront control system. The actuators operate at cryogenic and ambient temperatures, and have both coarse and fine

positioning capability. This configuration enables simple rigid body motion of the segments without distorting the segment surface. The secondary mirror has 6 actuators to provide 6 degrees of freedom motion, only 5 DOF is needed.

#### 4.6 Integrated Science Instrument Module

The ISIM contains three science instruments, the fine guidance sensor and a computer that directs the observatory in performing its daily operations. The three ISIM science instruments are a NIRCcam, a NIRSPEC, and a MIRI. Stored cryogenics are used for the MIRI with > 5 years of consumables. The individual science instruments are designed in response to the following goals for the future of space astronomy: “The observation of remote *galaxies in formation* – the assembly of matter and the first generation of stars in systems that will have evolved into galaxies like our own Milky Way, and the detection of *Earth-like planets* around other stars and the search for *evidence of life* on those planets.” - from *HST and Beyond*. Papers are presented at this conference on the NIRCcam, the MIRI and the FGS.

**Optical interface** – The optical interface to the ISIM is a curved-image focal plane located approximately 198-cm behind the primary mirror vertex. Of the overall 150-nm WFE allocation for the observatory, 56 nm of WFE is allocated to the ISIM for its alignment and internal distortions. The ISIM is supported off the rear of the OTE backplane by three kinematic mounts. This mounting configuration cleanly partitions optical and mechanical interfaces to simplify integration and test. The science instruments and FGS have non-overlapping FOVs. Simultaneous operation of all science instruments is possible. The FGS is used for “guide-star” acquisition and fine pointing. Its FOV is sufficient to provide a 95% probability of acquiring a guide star for any valid pointing direction. During normal observations, the FGS provides the pointing error signal used by the OTE and spacecraft to maintain a stable and accurate optical LOS.

**Packaging interface** – Our observatory architecture provides a 23 m<sup>3</sup> volume for the ISIM instruments, with 9 m<sup>2</sup> of radiator surface area dedicated to cooling the NIR detectors. The sides of the ISIM enclosure are also used to mount the focal plane electronics boxes and provide for their heat dissipation. The design of the enclosure allows these boxes to be placed in the way most convenient for the science instruments.

**Wavefront sensing and control interface** – The alignment and phasing of the OTE optics requires data gathered by the NIR Cam. Our optical design allows for a minimal set of requirements on these instruments. The only hardware required is the placement of five filters and a grism in the NIR Cam filter set. The physical positioning of these filters is no more exacting than those needed for science. During the WFS&C process, the NIR Cam will be operated in the same manner as when used for science (i.e., no special modes are necessary).

#### 4.1 Wavefront Sensing and Control Subsystem (WFS&C)

The ability to perform on-orbit alignment of the OTE is one of the enabling technologies GSFC identified as allowing NGST to be built within cost. The large telescope area is itself enabled by being populated with a number of smaller segments that can be manufactured and tested more easily than larger ones. The WFS&C subsystem aligns these segments so that their wavefronts match properly, creating a diffraction-limited 7-m telescope, not simply overlapping images from 36 individual 1-meter telescopes. Our architecture implements WFS&C in a manner that is simple in terms of hardware and algorithms, and accurate and deterministic in operation.

We chose 1-m semi-rigid segments specifically to limit segment-level wavefront errors to those that can be controlled through fabrication, radius-of-curvature adjustment, and rigid-body positioning. Our WFS&C does not require nor use any deformation of optical-structural surfaces. Such deformation cross couples surface corrections and limits the testability of the optic in the ground 1-g environment. Our semi-rigid mirror architecture supports use of a set of deterministic WFS&C algorithms that greatly simplify the fundamental and critical initial OTE alignment operation. Another benefit is use of a closed-form reconstructor algorithm to measure and correct segment-to-segment piston errors, a crucial initial operation in creating a phased primary mirror. WFS&C is done on the ground using the downlinked image data. Mirror adjustment commands are uplinked to the Observatory. Figure 16 summarizes the wavefront commissioning and maintenance flow.

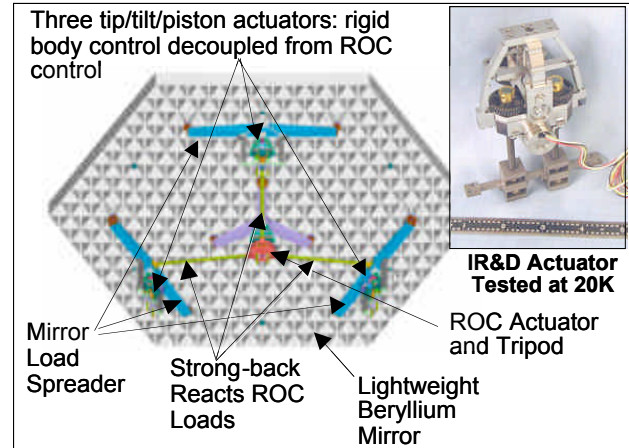


Figure 15. Primary Mirror Segment Actuator Placement

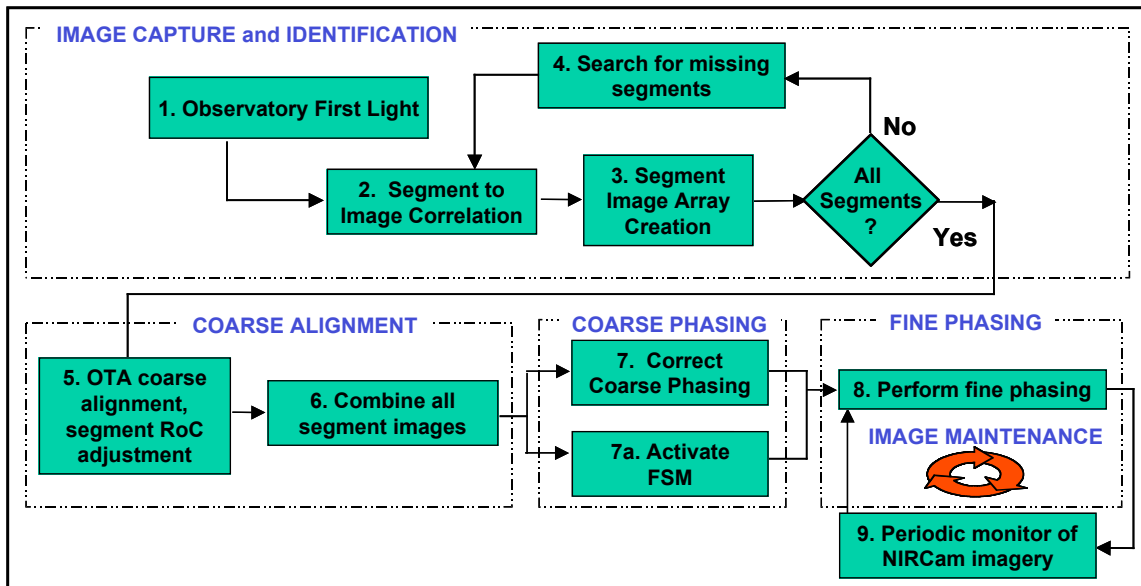


Figure 16. WFS&C Commissioning and Maintenance

The commissioning process is partitioned into four phases: (1) image capture and identification, (2) coarse alignment, (3) coarse phasing, and (4) fine phasing. We analyzed of the WFS&C architecture as well as implemented hardware/software demonstrations of the more critical aspects of this architecture. These analyses and simulations show that the residual errors from one step are well within the capture range of the next step. A separate paper is given at this conference describing the results of this modeling. The WFS&C process is straightforward, has a singular deterministic solution, and can be fully tested on the ground.

To accomplish commissioning, the OTE is pointed at a celestial region with specific characteristics at the 2  $\mu$ m NIRCcam operation wavelength. A bright (magnitude 10 or brighter) isolated commissioning star is located on the NIR Cam FPA. A second star (guide star), distant from the commissioning star by about 2 arcmin and approximately four magnitudes dimmer, is used with the fine guiding sensor. No other stars with brightness within six magnitudes of the commissioning star are allowed within 5 arcmin of the guide star. We have identified a number of star fields that meet these criteria to ensure availability regardless of the NGST launch date.

## 5. OBSERVATORY INTEGRATION AND TEST

We plan to use incremental verification on NGST the same way we used it on Chandra. Performance parameters are verified incrementally as the observatory is integrated to increase confidence in the final verification, while still allowing for a cost-effective and credible testing approach. This process stops at the highest level of integration that adequately verifies the system performance. All observatory-level test procedures and support equipment will have been used for lower level testing. By ensuring that all tests have been run before, and that no new equipment is used in this critical phase of the program, we minimize risk and reduce cost uncertainty.

Once each mirror element, with its actuators installed, successfully completes cryogenic tests, the mirror elements are attached to the backplane support structure and the OTE is aligned. A series of environmental tests are performed prior to verifying the OTE performance at cryogenic temperatures at the Plum Brook test facility at NASA's Glenn Research Center. The ISIM is installed and aligned. The OTE/ISIM combination is cryogenically tested and verified prior to integration to the spacecraft and sunshield. This OTE/ISIM cryogenic test is the end-to-end optical performance verification for the observatory. The Plum Brook facility (Figure 17) allows for high-fidelity testing of the Observatory. The large mass of the aluminum chamber wall resting on dampers creates a very low vibration disturbance, and an order of magnitude lower than any other chamber in the United States. The size of the test chamber (30.5 m diameter and 37.2 m high) gives adequate room to configure and build cost-effective assembly, test, and verification equipment. The size allows the flight design to proceed with minimal, if any, impacts due to limitations on the test facility size and configuration.

We test the OTE with the optical axis vertical (see Figure 17) to minimize gravity effects. Testing the optics in this orientation minimizes the moments induced in the mirrors at the actuator attachment interface. Moments at this interface can be very difficult to accurately back out analytically due to the sensitivity of the strain energy distribution to the local geometry.

Our OTE I&T approach results in a high-fidelity verification of the optical performance. Optical verification consists of three tests, two of which are performed simultaneously. The first test is for center of curvature by sensing the wavefront error of the entire primary mirror aperture at one time. By combining this result with the result of the sparse aperture test through the system, a complete evaluation of the optical performance of the system is obtained. Second, a sparse aperture test is performed where each segment is sampled in a single wavefront test (Figure 18). Our semi-rigid hexagonal primary mirror architecture allows us to use twelve 1-m flats rather than an expensive and high risk 7-m flat, or other higher risk concepts such as roving flats for the autocollimating return mirror. Another significant benefit of the sparsely sampled approach is that the autocollimating flats do not have to be phased to each other. We operate the test using individual triads of three primary mirror segments, allowing the mirror tip/tilt/piston to correct for phasing of the flats. Only stability of the flats is required. The semi-rigid nature of the primary mirror segments allows the influence of each actuator to be measured with high sensitivity.

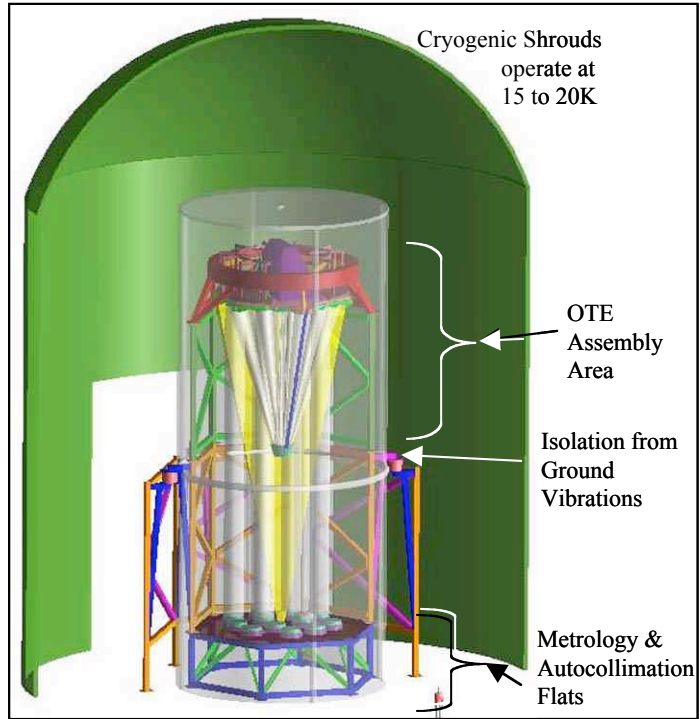


Figure 17. OTE Vertical Assembly and Test Tower in Plum Brook Cryogenic Chamber

The third test uses the NIR Cam to detect the end-to-end PSF created by the OTE and ISIM. Due to our simultaneous sampling over the full aperture of the telescope, the PSF shape is flight-like, with somewhat higher energy in the first ring than the flight PSF. This reduces significantly the test complexity, test risk, and cost. The third performance metric is a center of curvature (CoC) test that is performed simultaneously with the sparse aperture test.

The flight sunshield is tested in the deployed configuration in the Plum Brook chamber with a helium-cooled shroud. By performing a test of the sunshield against a helium-cooled shroud, we verify the thermal performance of the sunshield at operational temperatures.

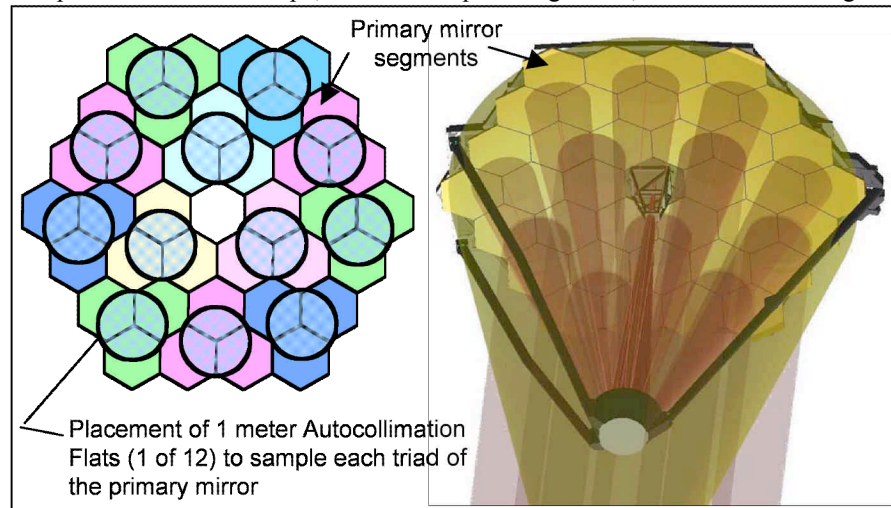


Figure 18. Full Aperture, Sparsely Sampled Testing Approach

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