High Resolution Structureless Telescope

Final Report

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1 Summary

An initial system architecture for the High Resolution Structureless Space Telescope[1] was created and evaluated. Some architectural changes have been made relative to the baseline design from the proposal. However, no "showstoppers" have been found to date. A new baseline has been created in which the multi-element primary mirror is stable with respect to the point mass forces from the Earth (i.e., each mirror segment moves in a Keplerian orbit). Thus, the only significant disturbance forces on the shaded primary mirror are higher order harmonics of the Earth and solar-lunar perturbations, all of which are very small in geosynchronous or Lagrange-point orbits. An off-axis Gregorian optical design has been created which, as a first estimate, will have a resolution on the Earth of 0.5 meters to 2 meters from GEO. Although substantial work remains to be done, at this time the design appears to be feasible and achievable with very substantial potential positive consequences for observations from space.

2 Status of Technical Work

All five tasks have been completed with the submission of this Final Report.

2.1 Task 1. Requirements Definition

The starting point of the study was to define requirements on the system performance and which are provided in the following table:

Parameter	Requirement
Telescope Location	Geosynchronous radius, 42,164 km Lagrange Point, L4 or L5
Resolution (Earth Observation Mission)	0.75 – 1.2 m

Table 1. System Requirements

From these system performance requirements, a series of telescope requirements were derived. These requirements were updated in the first Status Report from those given in the proposal and have not changed since then. The principal disturbance forces and torques are listed in Tables 2A and 2B.

2A. Disturbance Forces. Expressed as differential linear acceleration on two mirror segments 30 m apart and laser power required to balance the disturbance. Each 2-m diameter mirror segment is assumed to have a mass of 9.5 kg.

Disturbance Force	at GEO		at Earth-Moon L4	
	<u>Disturbance</u>	<u>Laser Power</u>	<u>Disturbance</u>	<u>Laser Power</u>
Sun	2.4×10^{-12} m/s^2	3.4 mW	2.4×10^{-12} m/s^2	3.4 mW
Moon	7.3×10^{-12} m/s^2	10.4 mW	5.2×10^{-12} m/s^2	7.3 mW
Earth (radial)	3.2×10^{-7} m/s^2	2.7 W	2.5×10^{-12} m/s^2	3.6 mW
Earth (E/W)	7.7×10^{-14} m/s^2	0.11 mW	Negligible	—

[1] Patent Pending

2B. Disturbance Torques. Expressed as worst case gravity gradient torque (mirror at 45 deg to torque source) on a 2-m diameter, 9.5 kg, mirror segment and required laser power on a control surface at the periphery needed to balance the torque.

Disturbance Torque	**at GEO**		**at Earth-Moon L4**	
	Disturbance	**Laser Power**	**Disturbance**	**Laser Power**
Sun	1.4×10^{-13} kg m^2/s^2	0.021 mW	1.4×10^{-13} kg m^2/s^2	0.021 mW
Moon	4.3×10^{-13} kg m^2/s^2	0.065 mW	3.0×10^{-13} kg m^2/s^2	0.046 mW
Earth (at 5º)	3.2×10^{-9} kg m^2/s^2	490 mW	4.3×10^{-12} kg m^2/s^2	0.65 mW
Earth (at 45º)	1.9×10^{-8} kg m^2/s^2	2.82 W	2.5×10^{-11} kg m^2/s^2	3.72 mW

Table 2. Principal Disturbance Forces and Torques on a Shaded Structureless Telescope in GEO and at the Earth-Moon L4 Lagrange Point.

Table 2 is an updated version from the proposal. Note specifically the major reduction in Earth (radial) disturbance forces relative to the proposal due to a revised telescope architecture. (See text for discussion.) Shade is assumed to block both solar radiation pressure and the solar wind.

The qualitative requirements included in the proposal have been replaced with actual values, as shown in Table 3.

	Source of Dominant	**Relative Position Requirement**				**Attitude Requirement**			
		Determination		**Control**		**Determination**		**Control**	
Element	**Requirement**	**Lateral**	**Radial**	**Lateral**	**Radial**	**Yaw**	**Roll/Pitch**	**Yaw**	**Roll/Pitch**
Primary Mirror Segments	Create Hi-Res Image	2 cm	**20 nm**	10 cm	**50 nm**	0.5 deg	**0.005 arc sec***	2 deg	**0.01 arc sec**
Secondary mirror	Point at target	0.5 cm	2 mm	1 cm	5 mm	0.05 deg	**0.02 arc sec***	0.1 deg	**0.05 arc sec**
FPU	See target	1 mm	2 mm	5 mm	5 mm	0.05 deg	0.5 deg	0.1 deg	1 deg
Mirror movers	Stationkeeping	1 cm	0.1 mm	10 cm	5 mm	0.01 deg	0.01 deg	0.1 deg	0.1 deg
Sun shade	Maintain shade	1 m	1 m	2 m	2 m	0.2 deg	0.2 deg	0.5 deg	0.5 deg
Control lasers	Point at laser tabs	2 cm	10 cm	2 m	2 m	0.5 deg	0.005 deg	1 deg	0.01 deg
Measurement lasers	Establish ref frame	0.5 mm	0.05 mm	1 m	1 m	0.01 deg	0.001 deg	0.05 deg	0.005 deg
Bus unit (if separate)	Talk to Ground Stat.	5 m	5 m	10 m	10 m	0.2 deg	0.01 deg	0.5 deg	0.05 deg

Note: 100 arc sec = 0.028 deg

All values are 3-sigma

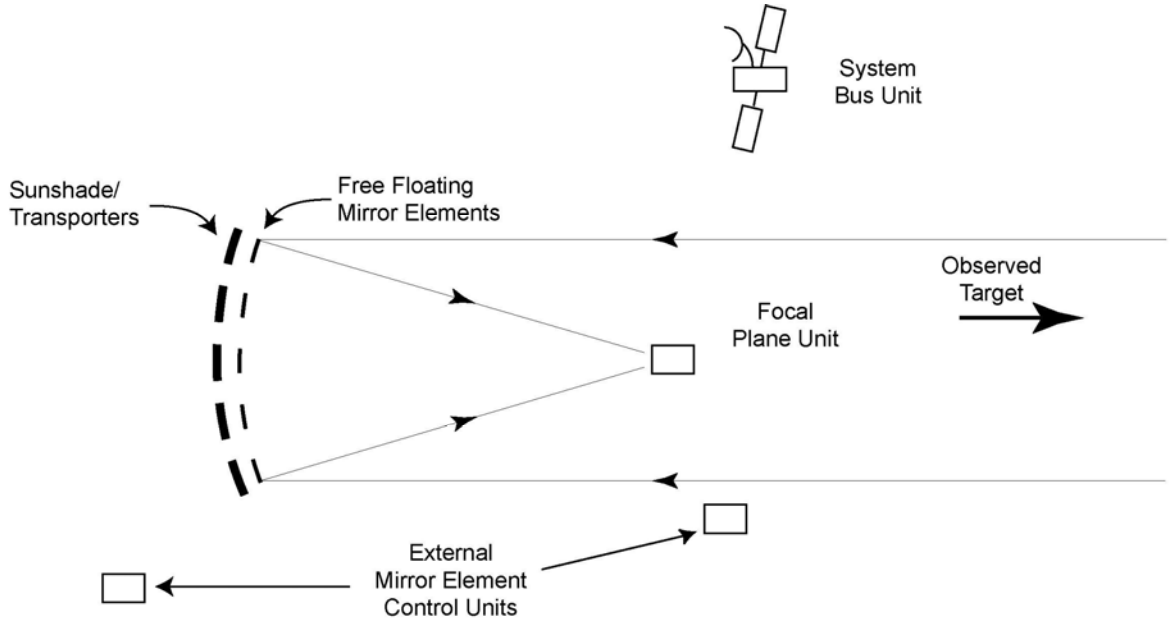
Tight requirements are shown in boldface

* Fine measurements are done by analysis of the image

Table 3. Position and Attitude Control Requirements

2.2 Task 2. Architecture Definition

The starting point for defining the architecture was the architecture described in the proposal and included below for reference (Figure 1).



<u>Sunshade/Transporters</u>
Serves to block mirror elements from both sunlight and the solar wind. May also serve as the transporter which will grab and hold the mirror elements when the system is reconfigured from one orientation to another. Provides propulsion and coarse control of both position and attitude.

<u>Mirror Elements</u>
Freely floating components with no active elements. Includes any secondary mirrors as well as the primary mirror.

<u>System Bus Unit</u>
This unit provides the basic bus functions for the entire telescope. These functions consist principally of the communications system and the control logic appropriate to operation of the telescope. It could be a separate spacecraft or a part of the focal plane unit or measurement and control units.

<u>Focal Plane Unit</u>
The actual collection instrument for the telescope. Position knowledge and control are similar to that of the mirror units. Attitude determination and control is only moderate. At a minimum this unit would have the focal plane array or other instruments and a means of reading and transmitting the results to the bus unit.

External Mirror
<u>Element Control Units</u>
Provide the lasers that ultimately control the mirror elements. There will be a minimum of 6 lasers essentially surrounding the telescope to provide both force and torque in both directions about all 3 axes. The lasers define the fundamental reference frame for the system and serve as both measurement and control devices. The position knowledge requirements on the lasers are very precise; however, the position control, attitude control, and attitude knowledge requirements are only moderate.

Figure 1. System Concept from Proposal

The principal changes in the architecture since the proposal involve the addition of an off-axis secondary mirror and incorporating a single cylindrical Sunshade to shield the Primary Mirror array from the Sun instead of individual Sunshades for each mirror. Minor additions were Rovers to allow repair or replacement of defective components. The architecture as it now stands is shown in Figure 2, which consists of 132 elements.

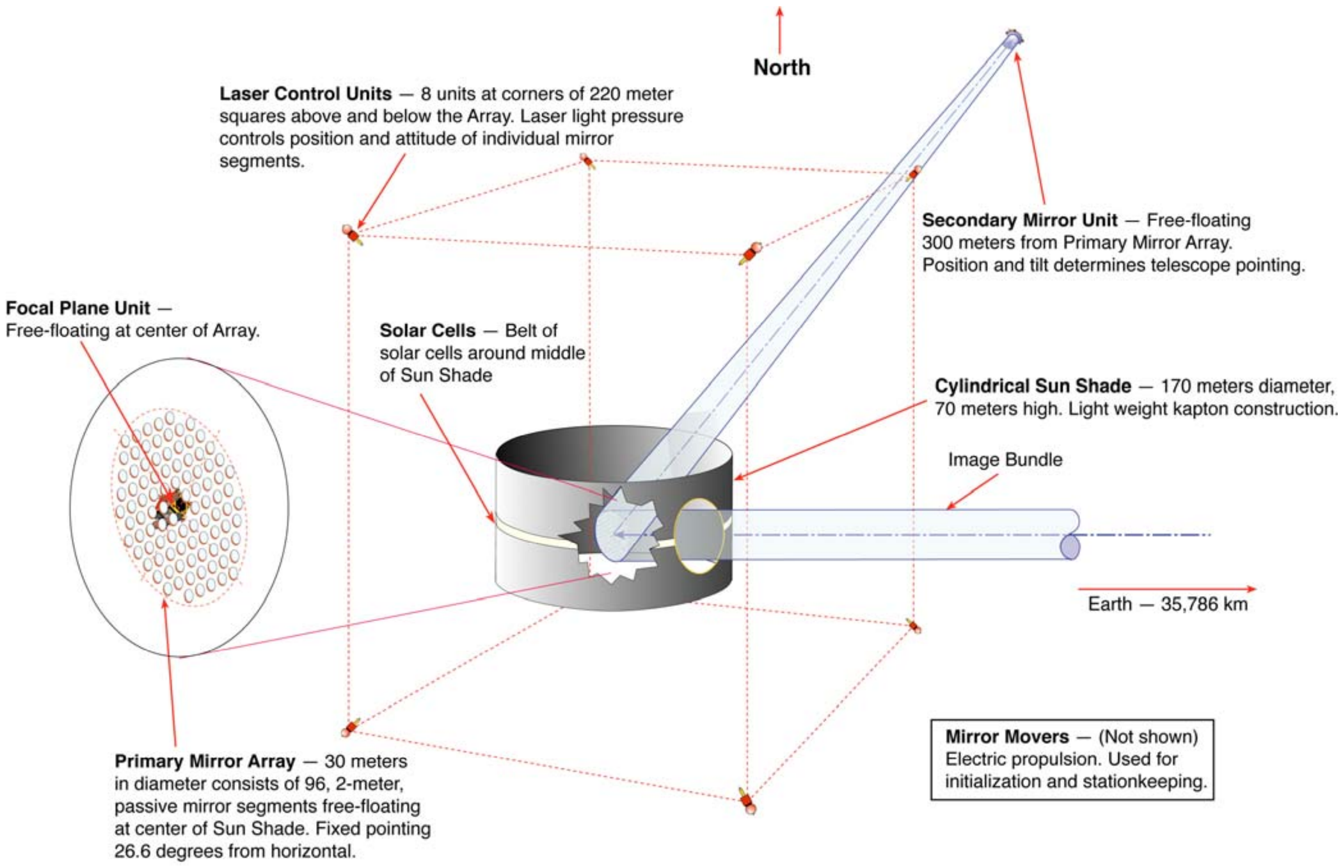


Figure 2. Structureless Telescope System

Each of the components of the system will now be described.

1. <u>96 2-m diameter passive Mirror Segments</u> – They are arranged in an array tilted 26.6 degrees back (i.e., away from the Earth) with a 3-m center-to-center hexagonal pattern (Figure 3). The segments are purely passive, with no electronics or controls. Each Mirror Segment has tabs on the edges for the control and measurement laser (see 5 below). There is also a steel wire loop near the center of the mirror to allow the Mirror Mover (see 6 below) to grab it. In addition, there is a set of current loops, powered by laser illumination on a solar cell attached to each segment, that provides for magnetic control that can be turned on and off, and which permits pushing or pulling on the mirror. Each mirror is estimated to weigh 9.4 kg, with launch loads distributed over the entire surface (i.e., the segments would launch stacked). On-orbit, the highest acceleration the mirrors would experience would be about 5 μg's. The optical surface of each Mirror Segment is currently spherical with a radius of about 630 m and a deviation from flatness of < 1 mm over the mirror surface. After the initial set-up, the mirrors will be shaded at all times (both operations and stationkeeping) and will have a temperature of about 40°K. The structure of the Primary Mirror can be changed or expanded by moving or adding mirror segments, which provides unique flexibility.

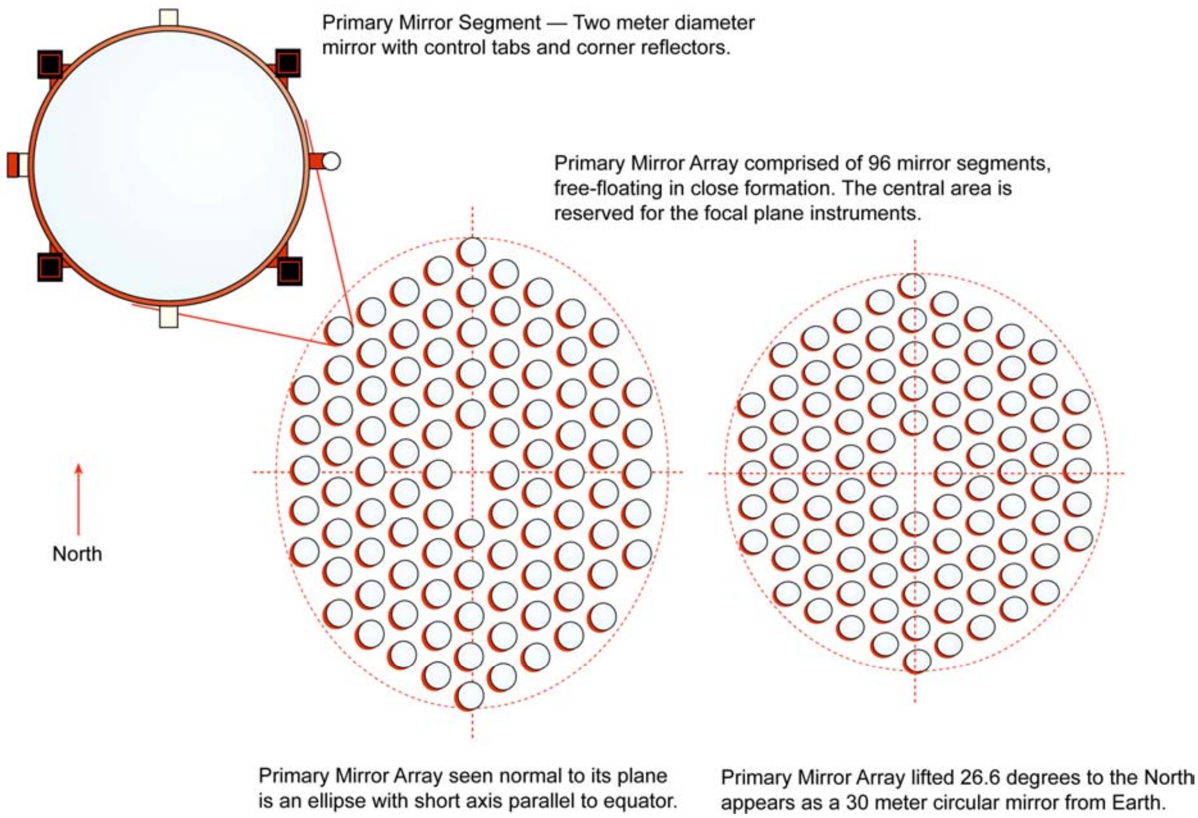


Figure 3. Primary Mirror Segment Layout

2. <u>1 Off-axis Secondary Mirror</u> that is 2 m to 3 m diameter (not yet finalized) – It will be located 300 m from the Primary Mirror (nominally 240 m above the orbit plane and 180 m in front) so that it does not block the incoming light path (Figure 4). The position and attitude of the secondary mirror points the telescope and brings the image back to the focal plane array near the center of the primary. Motion of the secondary mirror over the approximately 80 m diameter circle that represents the Earth disk provides the ability for repointing, scanning, mapping, and tracking. The secondary mirror is in a non-Keplerian, non-geostationary orbit and will require continuous force application to maintain its location. The force to maintain position = 0.0023 mN/kg or about 0.069 mN for a 30 kg secondary mirror. This force is easily imparted with electric propulsion. In addition, the plume will flow down and away from the Primary Mirror.

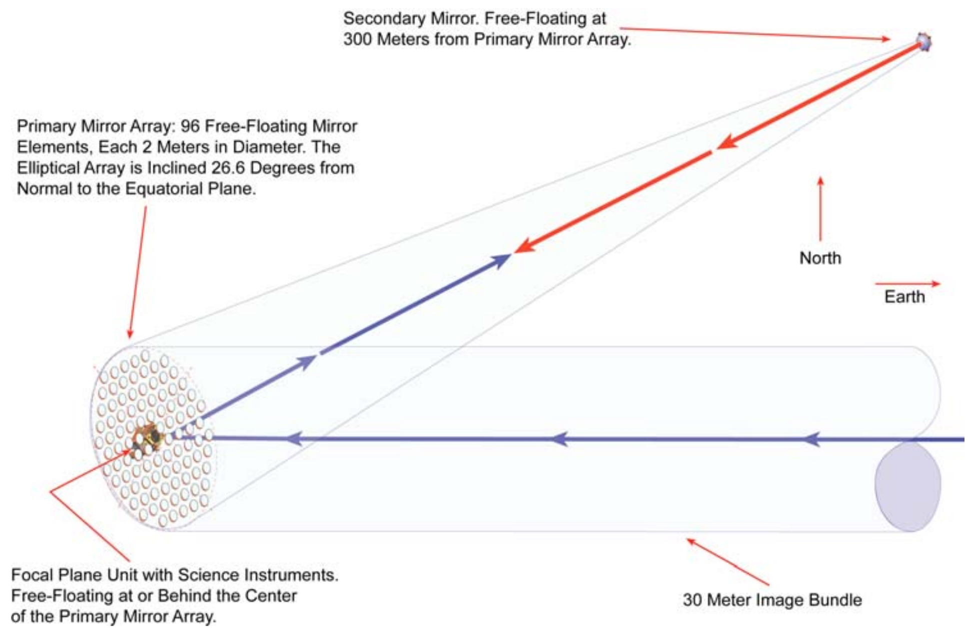


Figure 4. Secondary Mirror Optical Path

3. <u>18 Mirror Movers</u> (Figure 5) behind the mirror array that are used to grab onto and move up to 7 mirror segments at a time for stationkeeping and initialization. The system as a whole drifts north/south by up to 2 km/day, which must be corrected by regular stationkeeping maneuvers that require 6–8 hours if performed daily; 10–12 hours if performed weekly. The mirror movers utilize electric propulsion that has a maximum acceleration of about 5 μg's. The system moves together, but is not optically aligned during this process, while the main mirror array remains shaded. At the end of the stationkeeping maneuvers, the mirror movers provide coarse alignment, and a corrected tip-off rate to improve mirror alignment. They then move several centimeters away from the mirrors. Magnetic interaction with the mirror mover is used to bring the mirror segment relative rates to near zero; all magnetic interaction is then eliminated at the end of the initialization process.

4. <u>8 Control Lasers</u> – provide continuous fine control of the Primary Mirror segments during operations. They are arranged on the corners of two squares above and below the Primary Mirror array and could be free flyers or attached to the Sunshade (Figures 2 and 6). Control requirements on laser position and pointing are only moderate. The beams from the lasers can hit the sides of a control cube or corner retro-reflectors on the perimeter of the Primary Mirror segments. Each laser can hit each of the 96 Primary Mirror segments.

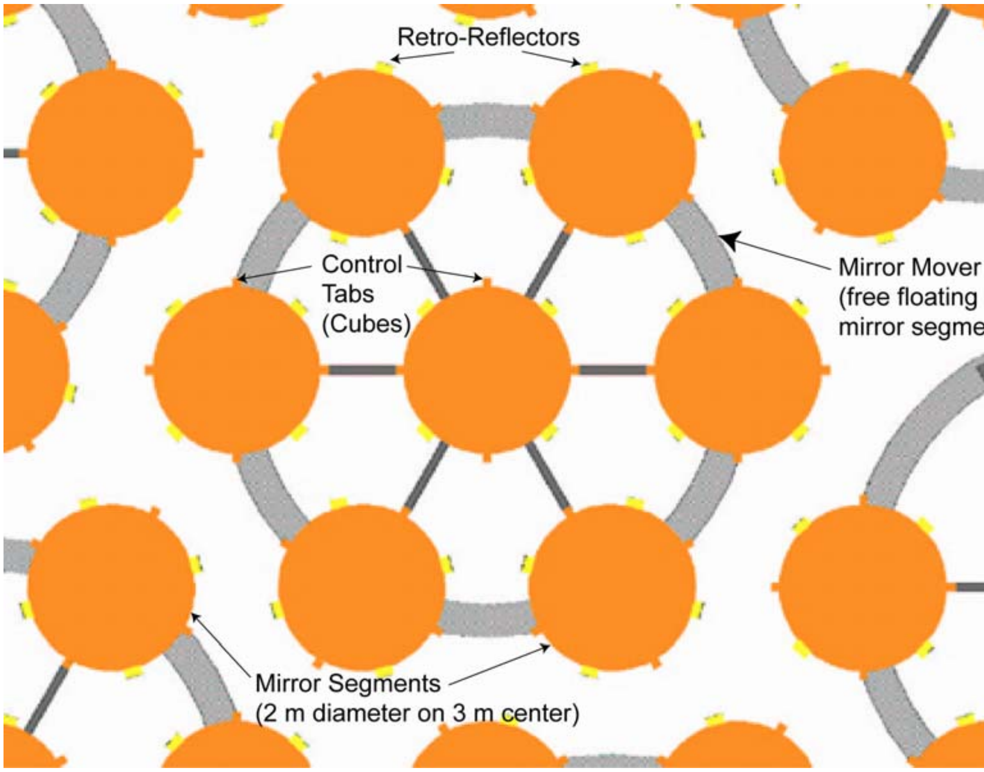


Figure 5. Mirror Movers with Mirrors

5. 3 Measurement Lasers – used in coarse alignment mode for measuring mirror positions for initialization and stationkeeping. They have insufficient accuracy for measurement during telescope operations.

6. 1 Sunshade – maintains the Primary Mirror, Focal Plane Units, and Mirror Movers in continuous shade and allows maintenance of the mirror segments at about 40°K (Figure 6). It has very modest position, attitude, and structure requirements. The dimensions have changed somewhat from the Strawman values and are now 170 m diameter and 70 m high. The Sunshade has an aperture hole for viewing to allow for a more structurally sound component and is open on the top and bottom. Solar cells are now located around the periphery of the shade; downlink antennas are mounted on the Earth-facing side on either side of the viewing hole; and the System Bus Unit (see 8. below) could also be mounted on the Sunshade.

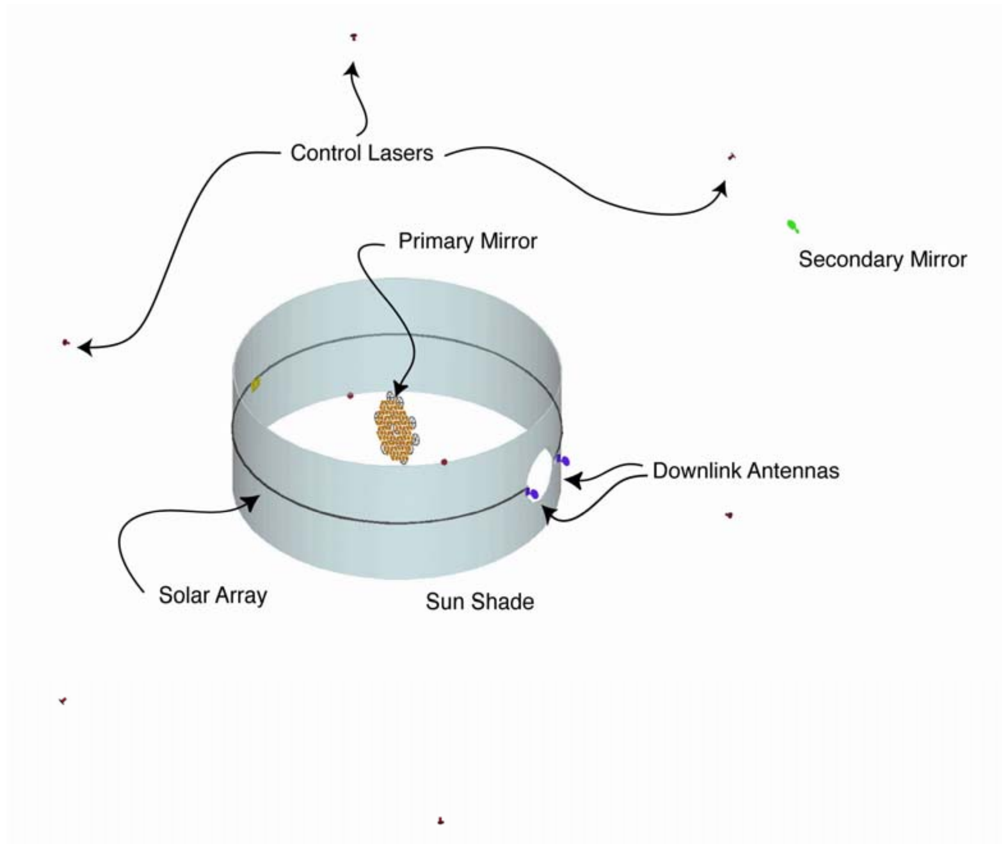


Figure 6. Sunshade and Control Lasers

7. <u>2 Focal Plane Units (FPU)</u> – at or near the center of the mirror array (may be at other locations, but would then require active control to maintain position, as with the secondary mirror). Image brightness should allow a frame rate of approximately 30 Hz. The in-focus region will be a circle approximately 25 cm in diameter, which allows many arrays to be incorporated in a single FPU. The 30 Hz frame rate will lead to very high data rate requirements. Data from the FPU is sent to the SBU for processing and transmission to the ground.

8. <u>1 System Bus Unit (SBU)</u> – provides basic services for the system: power, command and telemetry, central computing and decision-making, inertial orbit and attitude. It could be either integral to the Sunshade or a separate unit. On-orbit processing, data compression, and telemetry may be major issues because of the potential for truly enormous throughput.

9. <u>Power Transmission</u> – via microwave. The Mirror Movers need power, but are continuously shaded. The current solution is to generate power from solar cells located on the outside of the Sunshade, with power transmitters on the inside. Rectennas would be located on whatever equipment needs power. Overall transmission efficiency is taken to be 60%.

10. 2 Rovers – used for inspection and problem solving (e.g., removal of a defective unit). Conceptually, these rovers would be similar to the current MIT Spheres mini-spacecraft. They would include a thermal sensor, visual camera, and laser 3-D sensor, such as a unit that is built by Optech. They would also include a manipulator mechanism that would allow the Rover to grab other elements as needed. They would normally be docked on the SBU or Sunshade.

There is a combination of two independent motions that act on the mirror array that lead to the tilt angle introduced in the preceding paragraph. There is an out-of-plane motion that is sinusoidal along a line perpendicular to the base orbit plane (equatorial plane). In addition, the in-plane motion is an ellipse with its major axis in the in-track direction and the minor axis in the radial direction. The major axis is always twice the minor axis. In order to maintain the 2:1 ratio for this mirror array and still have a circular cross section as seen from the Earth, the tilt angle must be 26.6 degrees. Angles around 26.6 degrees will be investigated.

For a mirror array with a 30 circular cross section as seen from the Earth and tilted 26.6 degrees, the semiminor axis is 15 m, with a semimajor axis of about 17 m. The effect of the two independent motions just described is to cause all of the mirrors to rotate within an imaginary 15 m X 17 m ellipse at an angular velocity such that each mirror rotates around the interior of the ellipse once each day for the telescope located in a geosynchronous orbit (Note that the mirrors are not rotating about their individual centerlines.).

2.3 Task 3. Systems Engineering

2.3.1 Optical Design

The optical design is challenging in that it requires control of the mirror segments to approximately 50 nm in position and 50 nrad (0.01 arc sec) in angle. The system goal is to achieve 60%–70% of diffraction-limited performance, which is important because this range allows margin so that the system does not need to be perfect. The diffraction limit at nadir is about 0.7 m on the ground. Based on discussions with experts in optical design, including Michigan Aerospace, the goal is achievable given that measurement and control problems are workable.

The most challenging aspect of the optical design is the off-axis performance, which applies to the Earth observation application. The intent is to be able to work 8 deg off nadir to reach 25 deg elevation angle (ε) on Earth (Figure 3). The limits of good coverage would typically be between 20 deg and 30 deg in elevation angle. A fallback position would be to limit viewing to, for example, North America and move the Primary Mirror to view another region, such as South America. This movement would require about four hours to accomplish. The goal is consistent with work currently being done on liquid metal, typically Mercury, mirrors. The liquid mirror is formed by the equilibrium position of a rotating fluid sitting horizontally. Much of the work on liquid metal mirrors is currently being done at the University of Arizona and at INO in Canada. Advances expected during the next decade should permit the full 8 deg off nadir goal.

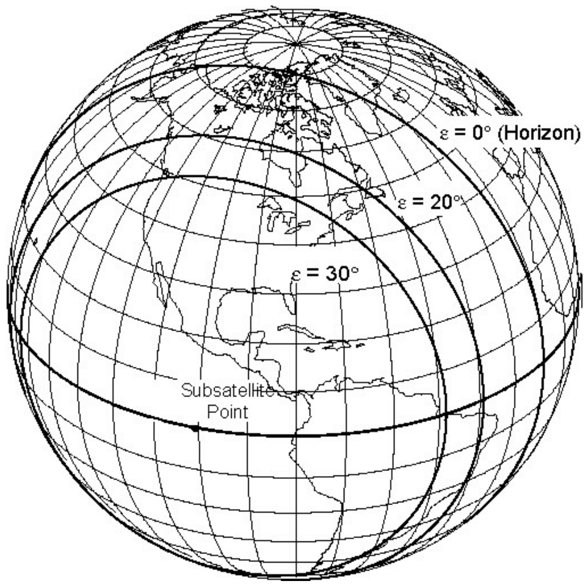


Figure 7. Representative Earth Coverage from GEO

2.3.1.1 Diffraction Limited Resolution

Starting with a Strawman telescope operating as an F/# - 10, a Gregorian off – axis parabolic layout was modified for initial calculations. The largest contributor of aberrations will be coma, as this layout is an off axis design. Off axis angles create coma error. Another option that will be analyzed is a design in which the focal plane is at the center of the mirror array (i.e., mirrors that would normally be at that location will be replaced by the focal plane.).

Three parameters were chosen to calculate which would shed light on the type of real aberrations to be expected:

1) Angular Astigmatic Blur,
2) Off axis sagittal Coma, and
3) System Modulation Transfer Function (MTF) – measure of system performance.

The first two parameters, which are third order contributors, place a limit to the spot quality of the system, which is less than 5 microns. The third parameter is an approximation of the image resolution, which is transferred through the optics. At 30% distortion loss, an MTF of 32.5 linepairs/mm is found. This calculates to a spot size of 15.4 microns, which seems like a reasonable spot quality for such a large system. By using a large aperture coupler at the focal plane, a conveniently sized flat image field can be generated, which allows the use of a larger pixel size, perhaps 25 microns. A system of about 8 million pixels would set an Earth Plane resolution of about 2 meters. If the overall wave front error can be held to ¼ waves, then the lower end resolution of 5 microns can be approached, which yields an Earth Plane resolution of about 0.5 meter. More analysis is required to converge on a more precise result. The largest contributor of aberrations will be coma, as this layout is an off axis design. Off axis angles create coma error.

2.3.1.2 Conceptual Design Ray Trace

The Gregorian telescope layout was chosen due to the degrees of freedom that will allow reduced aberrations (Figure 8). M1 is a large array of individual mirrors. For this analysis, each mirror was assumed to be 1 meter in diameter, and the array is laid out in an off axis parabolic (Note that at this level of analysis, whether the mirror is 1-meter or 2-meters in diameter does not impact the results. There would potentially be an impact on manufacturability and cost, however.). However, there may be some further reductions in aberrations with a hyperbolic curve. Each mirror is a simple spherical surface. The primary radius of the array is set at 600 meters with a conic of –1. The individual mirrors will have a radius of about 600 meters (620 meters radius was used for the calculations). Adjusting the radius a bit off of the primary array provides another tool for controlling aberrations.

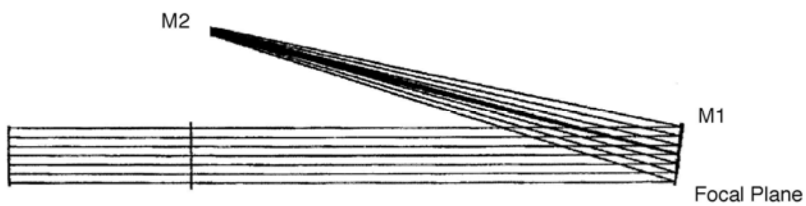


Figure 8. Gregorian Telescope Layout

A second mirror M2 sits just past prime focus of the array. This second mirror transfers the image back to the focal plane camera. The focal plane camera sits at the center of the mirror array M1. The mirror M2 possesses three degrees of freedom for correcting aberrations. It may be concave, convex, or plano. The conic factor for M2 can range from minus infinity to plus infinity. M2 may be situated on axis or off axis. The purpose is to have M2 do as much of the optics work as possible. It is helpful to have as large a diameter as possible (3.2 meters was used for calculations).

The third part of the telescope is a focal plane camera. The camera acts as a large aperture coupler between the CCD array and mirror M2, which provides the final aberration correction, most likely spherical aberration from the individual spherical mirrors. The purpose of the coupler is to keep the focal plane array looking at mirror M2. If the mirror array M1 is fixed and at its center is the focal plane camera, then all the image steering is accomplished by moving M2 only, which reduces the burden from M2 for positional accuracy at the focal plane. The larger the aperture at the coupler, the more forgiving the system (An 8 inch Double Gauss Lens running at F/# 5 was used for the calculations, but this may be some what limiting. More analysis is required.).

2.3.1.3 Viewing Angles and Adjustments

The first concern was to look at how much movement could be tolerated by the secondary mirror M2. Figure 9 is the loss of imaging light (Vignetting) as a function of lateral displacement. The plot displays a 'Knee' at 25%, which would just be detectable by a human eye. Up to 6 mm of lateral movement of M2 would not cause a serious loss if image quality.

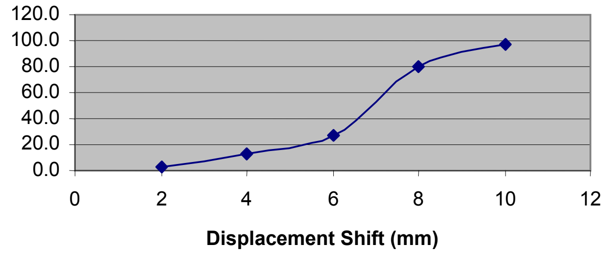


Figure 9. Vignetting Loss

The second set of data looks at the change of viewing angle as a function of arc displacement of mirror M2. A 1-degree position change of M2 requires an arc movement of 4.67 meters, which changes the Earth View by 625 km. An Earth View change of 20 km requires an arc shift of less than 3 inches.

2.3.1.4 Positional Sensitivities

First to be examined is the effect of individual mirror movements on image quality. Figure 10 plots spot size growth as a function of Z-axis displacement. For reference, within 10 % is considered normal for high quality laser optics. The 10 % mark lies at 18 mm displacement.

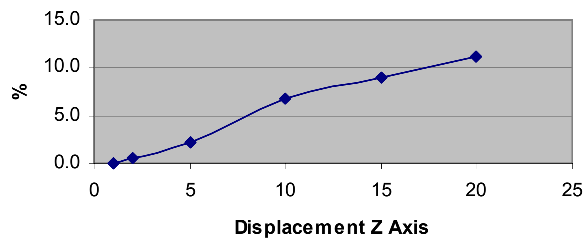


Figure 10. Spot Size Growth

Second to be examined is the effect of individual mirror angular deviations on image quality. Figure 11 plots Coma error as a function of angular rotation on an individual mirror. As the graph demonstrates, the coma error grows quickly, doubling in size from small angle deviations, less than 5 arcsec, which becomes the driving factor in creating a forgiving system. It may be that the choice of a large aperture coupler may have contributed substantial error and will be the subject of further study.

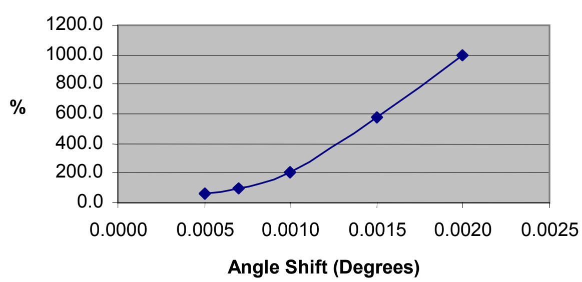


Figure 11. Coma Error

2.3.2 System Configuration and Motion of the Mirror Segments

2.3.2.1 System Weight and Power Budget

The weight and power budget for the components of the SST discussed in Section 2.3.1 are provided in Table 4 below. As can be seen, the entire SST is less than 5,000 kg and requires maximum power of about 32 kW (under 9 kW for stationkeeping. Neither of these values is large, even by today's standards, so that if they even doubled, the results would still be satisfactory. Given the surface area on the Sunshade, adding solar cells to generate more power (assuming other sources of power that are better are not ultimately used) is easy.

					Operating	Statnkping
Number	Component	Mass	Power	Tot Mass	Tot Power	Tot Power
		(kg)	(W)	(kg)	(W)	(W)
96	Mirror Segments	9.4	1	902.4	96	
18	Grabber/movers	38	75	689	1350	
	Grabber	30	70			
	Omni receiver	0.5	5			
	Power rectenna	5				
	EP Thruster	2.8	110.4	3.6	mN of Thrust	1988
	(inc EP for 7 mirror segs)					
1	Sun shade	160	5	160	5	
	Sun shade	150				
	Omni receiver	0.5	5			
	Power rectenna	5				
	EP Thruster	4.7	186.9	5.6	mN of Thrust	187
1	Secondary mirror	47	10	47	10	
	Mirror	40				
	Omni receiver	0.5	5			
	Power rectenna	5				
	Stationkpng EP Thruster	1.4	54.7	1.6	mN of Thrust	55
	Ops Control EP Thruster	0.1	4.6	0.1	mN of Thrust	
2	FPA	54	90	108	180	
	FPA	30	50			
	Att/Position Controller	15	25			
	Data Preprocessor	2	10			
	Transceiver	0.5	5			
	Power rectenna	5				
	EP Thruster	1.6	63.1	1.9	mN of Thrust	126
8	Control lasers	263	2305	2105	18440	
	100 W laser	200	2000	200	W output	
	Pointing Control Sys	50	300			
	Omni receiver	0.5	5			
	Power rectenna	5				
	EP Thruster	7.7	307.0	9.2	mN of Thrust	2456
3	Measurement lasers	5	26	15	78	
	1 W laser	1	10	1	W output	
	Omni receiver	2	10			
	Small rectenna	2				
	EP Thruster	0.2	6.0	0.2	mN of Thrust	18
2	Space Rovers	12	20	24	40	
	Optech + Vis Cameras	5	5			
	Thermal meas. Unit	3	5			
	Small rectenna	2				
	cold gas thrusters	2	10			
	Total received power				20,199	4,830
	Efficiency	65%				
	Total transmitted power				31,075	7,431
1	Bus Unit	620	825	620	825	825
	Bus Unit	300	500			
	Power Transmitter	50				
	Solar Arrays	207	based on	31,075	W prime power	
	Internal Telemetry	15	25			
	External Telemetry	30	300			
	EP Thruster	18.1	723.6	21.7	mN of Thrust	724
132	**Component Totals**	**1209**		**4671**	**31,900**	**8,979**

Table 4. SST Weight and Power Budget

2.3.2.2 System Cost Breakdown

Table 5 shows the estimated cost of the entire SST system that was described in Section 2.3.1, including non-recurring engineering, ground and on-orbit (LEO and GEO) tests, space segment build and deployment, 2 FPAs, the ground segment, and one year of operations. (Costs do not include the applications work that is done – i.e., applications planning and data reduction and analysis.) Costs are generally based on the Unmanned Spacecraft Cost Model (USCM) from SMAD III[2] for both non-recurring engineering (NRE) and total first unit (TFU) costs with a 90% learning curve applied for multiple, identical units. However, increased costs have been assigned for many units to account for increased development costs and the lack of design maturity at this stage. To facilitate comparison with the SMAD III cost model or others, the TFU cost per kg and average cost per kg are included in the two rightmost columns.

Although they represent only 20% of the total mass, the primary Mirror Segments are the principal drivers of the system mass, power, and cost. The mass of the mirror segments determines the size of the Laser Control Units that are, in turn, the principal mass and power determinants. Therefore, it is important to look very closely at the manufacturing of the Mirror Segments during the next study phase. Two key issues in making them lightweight are: (1) that they can be supported over the entire surface area during launch, and (2) that the largest acceleration that they will see on orbit is less than 10 micro-g's.

Note that the cost of space systems depends far more on how things are built rather than on what is built. Therefore, the way the program is run will be the major cost driver. Microcosm's main business area is reducing mission cost. However, reducing costs have not been applied in this case in order to obtain a conservative cost estimate.

Nmbr	Component	Unit Mass (kg)	Total Mass (kg)	NRE Cost ($M)	TFU Cost ($M)	Total Cost ($M)	Average Cost ($M)	TFU Cost/kg ($K/kg)	Average Cost/kg ($K/kg)
96	Mirror Segments	9	902	$10.0	$0.40	$19.4	$0.2	$43.0	$21.5
18	Grabber/movers	38	689	$15.0	$5.15	$59.7	$3.3	$134.6	$86.7
1	Sun shade	160	160	$4.0	$4.15	$4.2	$4.2	$25.9	$25.9
1	Secondary mirror	47	47	$3.0	$7.15	$7.2	$7.2	$152.6	$152.6
2	FPA	54	108	$31.0	$57.25	$103.1	$51.5	$1,058.7	$952.8
8	Control lasers	263	2105	$60.0	$21.15	$123.3	$15.4	$80.4	$58.6
3	Measurement lasers	5	15	$1.0	$1.63	$4.1	$1.4	$316.5	$267.8
2	Space Rovers	12	24	$6.5	$1.98	$3.6	$1.8	$165.0	$148.5
1	Bus Unit	620	620	$42.3	$51.00	$51.0	$51.0	$82.2	$82.2
132	**Component Totals**	1209	4671	$172.8	$149.86	$375.5	$2.8	$123.9	$80.4
	System Level Costs			$298		$298			
	NRE Systems engineering			$50					
	Ground Demos			$40					
	GEO Demo			$150					
	Ground system			$50					
	1 Year Ops			$8					
	Titan 4/Centaur (launch)			$500		$500			
	Total Costs			**$971**	**$150**	**$1,174**		**$124**	**$251**
	SST $K/kg			$143				$124	$80
	SMAD $K/kg			$101				$43	

Table 5. SST Cost Breakdown

[2] *Space Mission Analysis and Design, 3rd Edition*, ed. by W. J. Larson and J. R. Wertz, Microcosm Press, Torrance, CA; and Kluwer Academic Publishers, Dordrecht, The Netherlands, 1999.

2.3.2.3 Motion

The telescope motion is most easily thought of as the sum of large-scale motions that move the whole telescope and much smaller perturbative motions that disrupt the structure of the telescope. Note that this motion is not quite the same as Keplerian motion plus perturbations. Some perturbations move the whole telescope. Some Keplerian motion disrupts the telescope structure. Refer to the force and torque budgets listed in Tables 2A and 2B, respectively.

2.3.2.3.0 Large-Scale Motion

The whole telescope is in a nearly circular, near zero inclination, geosynchronous orbit moving at 3.075 km/sec in inertial space. The degree to which the fundamental orbit is not circular or not zero inclination moves the whole telescope slowly with respect to the Earth's surface, but does not disrupt the telescope structure. The largest perturbation to this Keplerian orbit is the N/S drift due to the Sun and the Moon, which may be as large as about 2 km/day, which causes a need for regular stationkeeping, but does not disrupt telescope structure. There is a similar, but smaller, E/W effect due to out-of-roundness of the Earth's equator. Solar radiation pressure would ordinarily be the next largest perturbation, but is mitigated on the Primary Mirror, FPU, and Mirror Movers by the Sunshade. Solar radiation pressure must be accounted for in the motion of the secondary mirror, Sun shade, and control lasers

2.3.2.3.1 Small-Scale Motion

There are two primary disruptive forces on the telescope – differences in the orbital elements and tidal forces from the Sun and Moon. Lunar radiation pressure, self-gravitation, and other small forces exist, but are much smaller and are accommodated by the active control system. Differences in orbital elements have an impact because different parts of the telescope are at different locations, both radially and N/S, which means that the Keplerian orbital elements will be slightly different. Unperturbed Keplerian motion results in a sinusoidal N/S motion and an in-plane elliptical motion with the E/W axis of the ellipse twice as long as the radial axis. If the segments that make up the Primary Mirror are tilted 26.6 deg to nadir, then the unperturbed motion will be an ellipse with a circular projection in the horizontal plane. The net effect is that the Primary Mirror appears to rotate once per orbit about its central axis, like a solid object, but this rotation is stable and does not affect the telescope "structure". Without the chosen mirror design, differences in orbital elements would be by far the largest disturbance on the Primary Mirror and would make the problem much harder.

Solar/lunar tidal forces

There are very small differential solar and lunar tidal forces that arise from the fact that different parts of the Primary Mirror are closer than other parts to the Sun and to the Moon. These are the largest disturbances to be countered by the control lasers and require mW of laser power per mirror segment.

2.3.3 Motion and Placement of Ancillary Elements

Differences in orbital elements require continuous stationkeeping on the secondary mirror that is in a non-Keplerian orbit. They are accommodated in the secondary mirror control budget. Likewise, the Mirror Movers, Sunshade, Control Lasers, Mirror Movers, Measurement Lasers, and SBU will require continuous stationkeeping.

2.3.4 Control and Estimation System Analysis

2.3.4.1 Initial Statement of the Control Problem

The basic or essential control problem can be stated in two parts:

1) "Control the linear and angular positions of a set of free-flying mirror segments with respect to a desired 3-D telescope primary mirror surface or shape within tenths or hundredths of a wavelength of light using the force exerted from several laser control units near the mirror segments."
2) "Control the linear and angular position of a free-flying focal plane or science camera unit in order to receive and focus the image created by the telescope primary mirror."

These free-flying mirror segments and focal plane unit form the basis of a telescope that will be used either for earth imaging in geo-synchronous equatorial orbit or for celestial observations in a stable earth-moon Lagrange orbit. This discussion will focus only on the earth imaging option.

2.3.4.2 Control Problem Decomposition

The control problem will be decomposed in terms of overall system control objectives and individual object control objectives. Functionally, the control problem can be decomposed into familiar functional analysis patterns:

1) Control
   - Input Application: generation of forces and moments, voltages, etc., which cause a state transition other than those caused by initial conditions
   - Guidance: determination of the desired state trajectory (servo commands)
2) Estimation
   - Targeting: estimation of the target or final state for a terminal controller and the nominal or desired steady-state for a regulator
   - Navigation: estimation of the state of the system to be controlled

2.3.4.3 System Control Objectives

The overall objective of this system is essentially to use an optical telescope to create a high-resolution image that can be acquired and translated into useful information for various system users. For the earth imaging in geo-synchronous equatorial orbit option, the resolution objective is about 1.5 meters. It is desirable to have a field of regard that includes all of the Earth that is visible at this point in orbit.

2.3.4.4 Objects to be Controlled

The telescope system is essentially a distributed system consisting of several collaborating objects, most of which are free-flying spacecraft (or just objects in orbit). This section is a breakdown of the currently identified objects in the design baseline that will need to be controlled in order to meet the overall system control objectives.

2.3.4.4.0 Primary Mirror Segments (PMS)

There are 96 primary mirror segments (PMS), arranged as depicted in Figure 3. Each PMS is 2 meters in diameter and is separated by 3 meters center-to-center. The resulting telescope primary mirror (PM) is about 30 meters in diameter with a fill factor of about 40%. There are no electrical, mechanical or electronic systems contained in each mirror. There are four corner reflectors, arranged so that two sets of reflectors are aligned with the plus and minus y or pitch axis directions and two sets are aligned with the plus and minus z or yaw axis directions (See Figure 12). There is a black roll alignment tab located next to the + y-axis reflector. There are also four control tabs, spaced at 45 degrees from the corner reflectors. The rear of a PMS has a small magnetically sensitive circular area in the center where the electromagnet of a PMS transporter can dock and undock.

2.3.4.4.1 Secondary, Tertiary and Quaternary Mirrors (SM, TM or QM)

A secondary mirror may be needed for the telescope optical design (part of the Strawman design), along with potential tertiary and quaternary mirrors. One of these mirrors may need to be deformable to provide wavefront control. The deformable mirror could be a continuous surface or a set of smaller mirrors. The secondary mirror will be free flying, but the tertiary and quaternary mirrors are likely to be part of another unit, such as the focal plane or science camera unit.

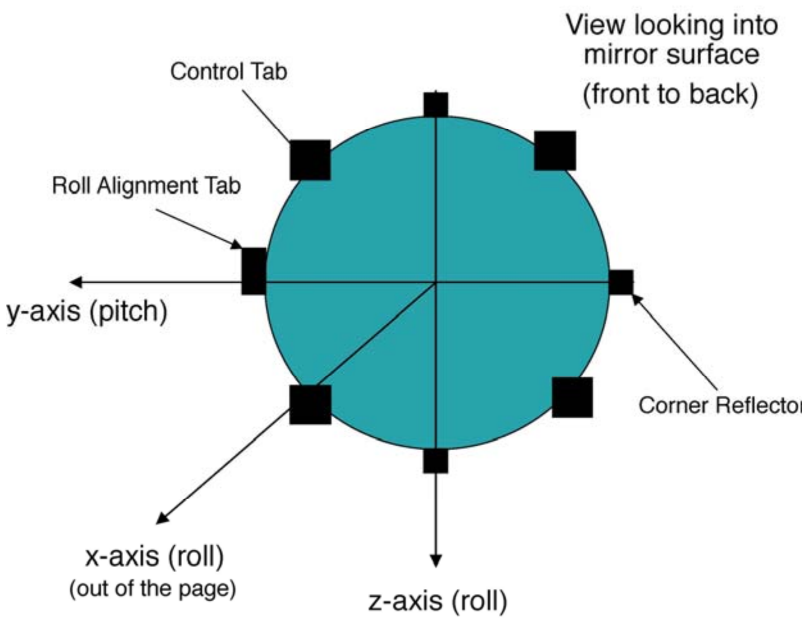


Figure 12. Primary Mirror Segment (PMS)

2.3.4.4.2 Focal Plane or Science Camera Unit (FPU)

The free-flying unit containing the focal plane sensor or science camera will have its own GN&C capability.

2.3.4.4.3 Shape Reference Control and Estimation Unit (SRCEU)

This free-flying unit is located at the reference point for the desired mirror shape. Its purpose is to estimate the linear and angular deviations of the primary mirror segments and transmit control commands to the laser control units. It has a low-power imaging laser range finder that will create a measured 3-D image of the primary mirror segments, referenced to the shape reference frame, for which the origin is the shape reference point. It also has a small camera for determining the location of the black roll alignment tabs on the primary mirror segments. It is envisioned that the shape reference point will be along the telescope optical axis, at some appropriate distance in front of or behind the primary mirror segments.

2.3.4.4.4 Laser Control Units (LCU)

Several (eight in the Strawman concept) free-flying laser control units will be located behind and above the sunshade. It is envisioned that four will be above the sunshade and four below the sunshade, for a total of eight. They will shoot laser beams over the top of the sunshade to exert forces and moments on the primary mirror segments. Each unit will have GN&C capability and a communication link with the shape reference control and estimation unit.

2.3.4.4.5 Sunshade (SS)

This is basically a large cylindrical thin-walled tube that shades the PMSs from the sun. It is open on one end to allow light from the primary mirror to reach the focal plane unit. The sunshade will have GN&C capability.

2.3.4.4.6 Artificial Guide Stars (AGS) (Optional)

If wavefront control is required, then one or more artificial guide stars will be needed. These are free-flying units that are located behind the focal plane or science camera unit. Their purpose is to emit a bright light that will be reflected off of the primary mirror and ultimately on to a deformable mirror and a wavefront sensor. They will be arranged to optimize the effectiveness of wavefront sensing and control. Each AGS will have GN&C capability.

2.3.4.4.7 Primary Mirror Segment Transporter Units (PMSTU)

The initial deployment and alignment of each PMS will be performed with some free-flying transporter units. Each unit will have GN&C capability and a communication link with the shape reference control and estimation unit. These units dock and undock with the PMS using an electromagnet.

2.3.4.4.8 Power Generation and Distribution Unit (PGDU)

It is envisioned that a separate free-flying unit will be needed to generate and provide electrical power to several of the objects in the system. Solar power using large arrays may be adequate and the generated power will be transmitted through a microwave link. This unit will have GN&C capability.

2.3.4.5 System Control Modes

2.3.4.5.0 Initial Deployment and Alignment

The objective of this mode is to set up the initial positions and attitudes of the various system objects (See Figure 1). Except for the primary mirror elements, all objects can move themselves. The mirrors will be moved with PMS transporter units. A PMSTU with the attached PMS essentially flies a rendezvous trajectory to the origin of the shape frame for a PMS and then aligns the PMS with the orientation of the shape frame. This rendezvous and alignment is done with guidance information from the SRCEU.

2.3.4.5.1 Coarse Shape Regulation

After the PMS transporter units have undocked at the completion of the rendezvous and alignment, the coarse shape regulation mode begins. Figure 13 shows a two-dimensional view of a representative set of PMS positions and attitudes with respect to the desired primary mirror shape at the start of the coarse shape regulation mode. Each PMS is modeled as a rigid body with six degrees of freedom (12 state variables). As shown in Figure 14, a body-fixed Cartesian coordinate frame, called the mirror frame (for PMS i), is located at the center of each PMS. A separate shape frame, which represents the desired position and orientation for each mirror, is defined for each mirror frame. Figure 14 also shows the shape reference frame, which is used as reference for the desired shape of the mirror. The measurements of the position and orientation of each PMS are referenced to the shape reference frame. The regulation task is to minimize the deviations of each PMS (the mirror frames) with respect to the shape frames. The state of each PMS is estimated by the SRCEU using a Kalman filter that processes imaging laser measurements and camera images. The estimated state and error covariance matrix for each mirror are entries or elements in a 96-element (one for each PMS) target track file database maintained by the SRCEU. This approach allows the state of each PMS to be estimated without continuous measurement data, since the filter will propagate the state between measurement updates. PMS state is controlled using the laser control units (LCU), which process commands from the SRCEU.

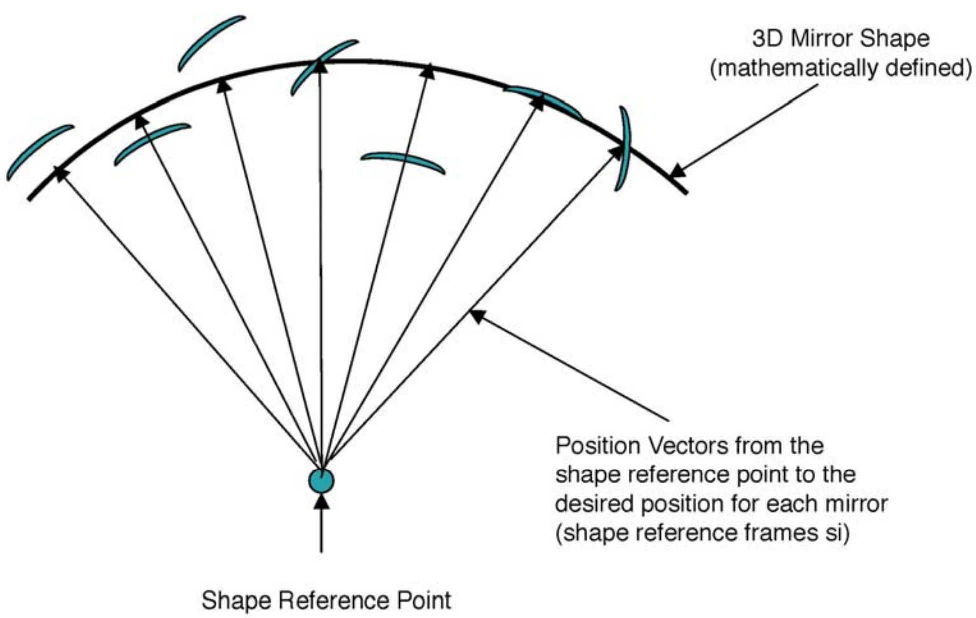


Figure 13. Coarse Shape Regulation

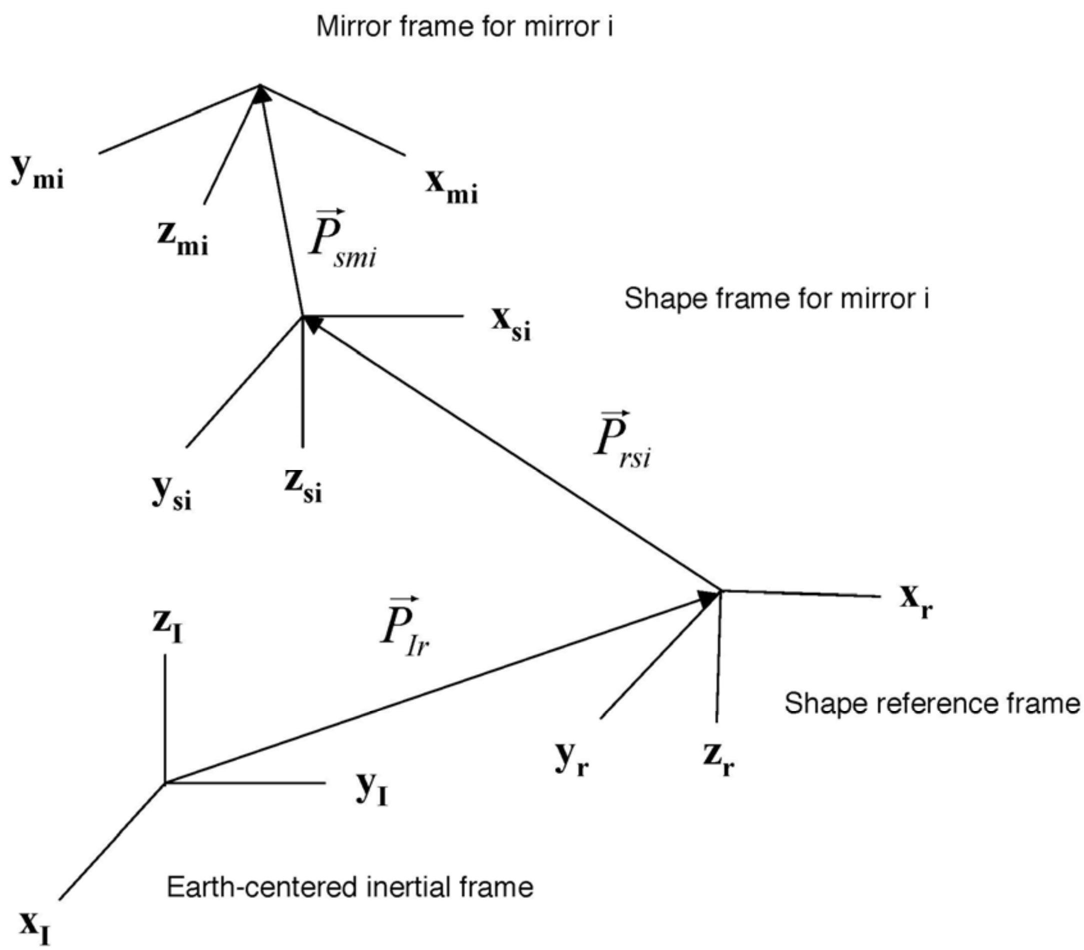


Figure 14. Coordinate System Definitions

2.3.4.5.2 Fine Shape Regulation

When the coarse shape regulation control mode reaches a steady-state condition, and the system is ready for operation, the fine shape regulation mode begins. Like the coarse shape regulation control mode, the LCUs are used to control the state of each PMS. The difference is that in the fine mode, a wavefront sensor is used to measure the distortion in the wavefront due to control errors in the coarse mode. Refer to Figure 15 for a schematic of an adaptive optics system using a wavefront sensor and a deformable mirror. The principle is the same for the fine shape regulation mode, except that the adaptive mirror is actually the primary mirror and the light from the telescope is actually the light from an artificial or real guide star. The entire issue of wavefront control will be examined closely in the next phase to determine if the capability is even needed.

2.3.4.5.3 Deformable Mirror Wavefront Control

This mode is entered if the system needs to use a deformable mirror to achieve the desired system performance. In this mode, the coarse shape regulation mode remains active, even during periods of system imaging operation.

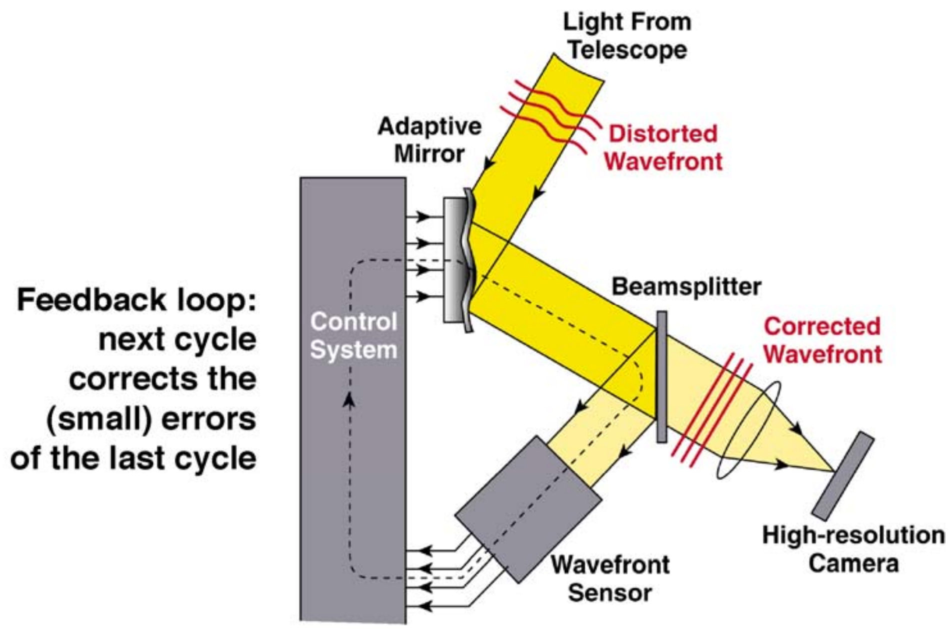


Figure 15. Representative Adaptive Optics System

2.3.4.5.4 Control Laser State Regulation

Since the SRCEU provides the commands and control loop closure for PMS fine and coarse shape regulation, the position of the LCUs with respect to the mirrors does not need to be known or controlled accurately. The attitude of the LCUs with respect to the mirrors does need to be known and controlled accurately in order for the laser beams to hit the control tabs on each PMS.

2.3.4.6 Sensor Hardware

Some candidate system sensor hardware will be discussed in this section.

2.3.4.6.0 Imaging Laser Rangefinder

Bosch makes an ultra-stable space qualified Nd:YAG NPRO (Non Planar Ring Oscillator) Laser Head. It has an emission frequency of 281 THz (1064 nm) and 100mW of emission power. The emission is ultra-stable with $\Delta f/f < 10^{-11}$ free running. This unit should be capable of ranging accuracy in the neighborhood of 1/10 of the wavelength of 1064 nm, or about 100 nm. An imaging laser system could be designed and built around this laser head. There may be some development work required to obtain a fast and accurate pulse generation and counting unit or some kind of phase-locked loop for phase measurement.

2.3.4.6.1 Wavefront Sensor

Several wavefront sensors have been built for and used by ground-based telescopes, such as the Keck 10 m telescope, the 6.5 m MMT telescope and the Palomar 200 inch telescope. One or more of these could be adapted for space use.

2.3.4.7 Control Requirements During Operations Mode

The control requirements on most components are modest because most components are not a part of the optical path and have no direct connection to the optical components. This situation allows substantially less stringent requirements than for most telescopes. The most stringent requirements are on the roll and pitch attitude components of the Primary Mirror segments. Optical analysis shows only modest relative position requirements on the mirror segments, even in the radial direction. Controls analysis (see below) shows very low frequency requirement on mirror segment attitude motion, which allows laser control of multiple elements. Table 6 (duplicate of Table 3 – included here for ease of reference) lists control requirements on each of the principal components of the SST.

	Source of Dominant	Relative Position Requirement				Attitude Requirement			
		Determination		Control		Determination		Control	
Element	Requirement	Lateral	Radial	Lateral	Radial	Yaw	Roll/Pitch	Yaw	Roll/Pitch
Primary Mirror Segments	Create Hi-Res Image	2 cm	**20 nm**	10 cm	**50 nm**	0.5 deg	**0.005 arc sec***	2 deg	**0.01 arc sec**
Secondary mirror	Point at target	0.5 cm	2 mm	1 cm	5 mm	0.05 deg	**0.02 arc sec***	0.1 deg	**0.05 arc sec**
FPU	See target	1 mm	2 mm	5 mm	5 mm	0.05 deg	0.5 deg	0.1 deg	1 deg
Mirror movers	Stationkeeping	1 cm	0.1 mm	10 cm	5 mm	0.01 deg	0.01 deg	0.1 deg	0.1 deg
Sun shade	Maintain shade	1 m	1 m	2 m	2 m	0.2 deg	0.2 deg	0.5 deg	0.5 deg
Control lasers	Point at laser tabs	2 cm	10 cm	2 m	2 m	0.5 deg	0.005 deg	1 deg	0.01 deg
Measurement lasers	Establish ref frame	0.5 mm	0.05 mm	1 m	1 m	0.01 deg	0.001 deg	0.05 deg	0.005 deg
Bus unit (if separate)	Talk to Ground Stat.	5 m	5 m	10 m	10 m	0.2 deg	0.01 deg	0.5 deg	0.05 deg

Note: 100 arc sec = 0.028 deg Tight requirements are shown in boldface
All values are 3-sigma * Fine measurements are done by analysis of the image

Table 6. Position and Attitude Control Requirements

The basic concept behind the Primary Mirror segment control concept is to apply a small control torque on a Primary Mirror segment using applied forces acting on control tabs at apposite ends of the segment. Two lasers will be used to generate the applied forces for each axis of control. There will be two axes of control, which are normal to the axis of symmetry of the mirror element. A minimum of four lasers will be required to generate control torques for all 96 mirror segments, since the control torques will act on only one mirror segment at a time. The additional four lasers add redundancy, are needed operationally so the Sunshade does not block the optical path of the lasers, and allow positioning of the lasers so no reflected laser light interferes with the telescope optics. Each of the 96 segments will be controlled in a sequence that repeats over some specified interval of time. Each mirror segment, then is actively controlled for only (1/96)*100 or about 1 percent of the time. For the other 99 percent of the time, each mirror segment is coasting between control torque applications. The coast dynamics are determined by the moment of inertia of the mirror segment and the disturbance torque. This control strategy requires an estimate of the appropriate amount of angular impulse (torque times application time), the direction or orientation and when to apply it.

To illustrate the control concept, consider Figure 16. This figure is a single-axis model of the angular state of the mirror segment. The upper plot shows the angle deviation from some desired reference, and the middle plot shows the angular velocity. The lower plot shows the angular acceleration caused by the sum of the disturbance and control torques, where the disturbance torque causes a positive rotation and the control torque causes a negative rotation. The control objective in this case is to keep the angular deviation within +/– 1 arc sec. The mirror segment starts at the maximum negative angular deviation limit at zero angular velocity, driven only by a very small angular acceleration caused by the disturbance torque. Just before the angular deviation reaches the maximum positive limit at about 120 sec, the control beams from the lasers are moved into place on the control tabs, and the control torque is applied. This control torque is applied over a time interval that is long enough to reverse the sign of the angular velocity that occurs when the mirror segment reaches the maximum positive limit. The mirror segment is then allowed to coast, while the lasers are moved and used to control the remaining segments. Note that the initial condition repeats at about 240 sec, which is the revisit or cycle time for this particular control situation. The control is applied again at about 360 sec.

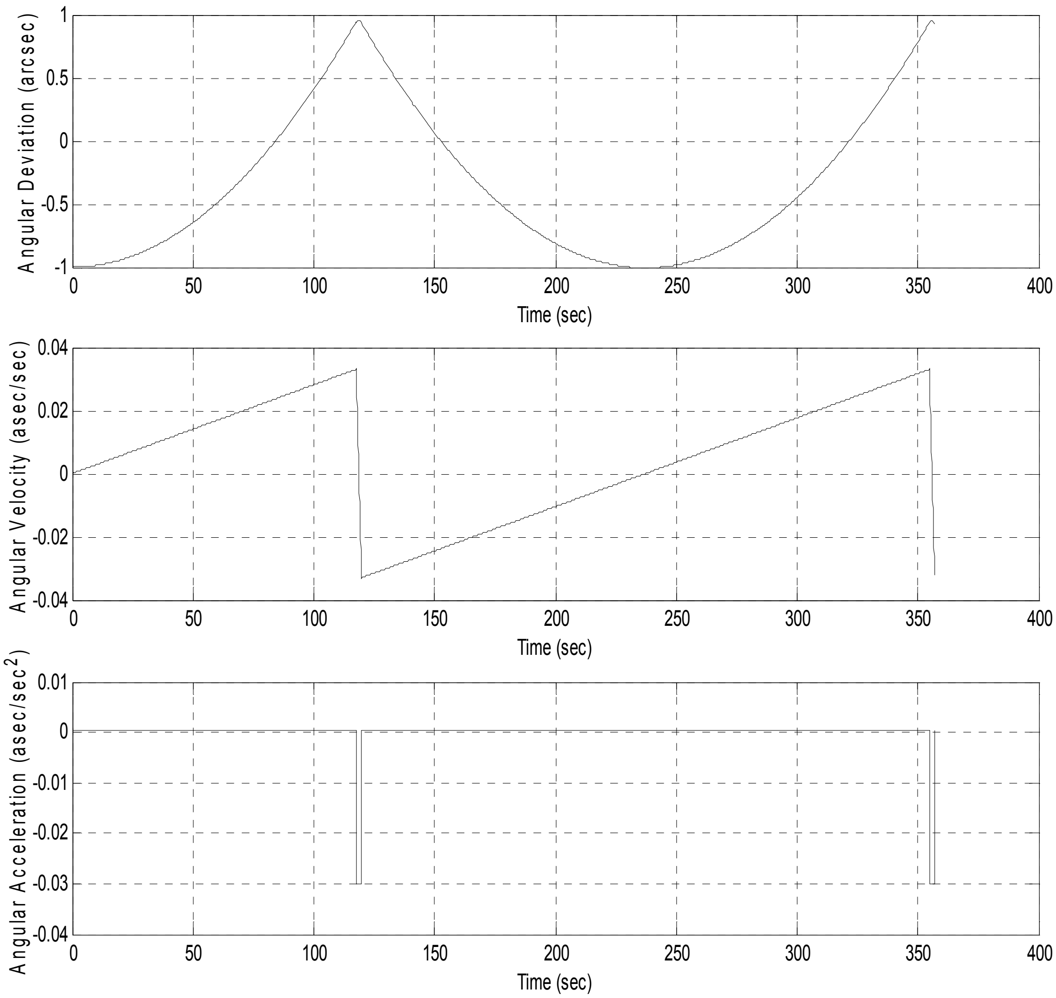


Figure 16. Illustration of Mirror Segment Control Concept

A conceptual, single-axis general control algorithm was derived that is a function of the:

1. disturbance torque
2. mirror segment moment of inertia about the control axis
3. maximum angular deviation limit
4. number of mirror segments
5. ratio of laser beam move time to fire (or control application) time for a mirror segment

This control algorithm computes the:

1. ratio of control torque to disturbance torque
2. laser control application lead angle (when to start the move to the segment control tabs)
3. laser control application interval (fire time)

The ratio of control torque to disturbance torque is given by:

$$f = n_{seg}\left(\frac{\Delta t_{move}}{\Delta t_{fire}} + 1\right)$$

where:

n_{seg} = number of mirror segments
Δt_{move} = move time interval
Δt_{fire} = fire time interval

The laser control application interval (fire time) is given by:

$$\Delta t_{fire} = \frac{4}{\sqrt{f(f-1)}}\sqrt{\frac{\theta_{\lim}}{\dot{\omega}_{dist}}}$$

$$\dot{\omega}_{dist} = \frac{T_{dist}}{I_{\theta}}$$

where:

θ_{lim} = maximum angular deviation limit
T_{dist} = disturbance torque
I_{θ} = mirror segment moment of inertia about the control axis
$\dot{\omega}_{dist}$ = angular acceleration caused by disturbance torque

The laser control application lead angle (when to start the move to the segment control tabs) is given by:

$$\Delta\theta_{lead} = \omega_{\lim}\frac{\Delta t_{fire}}{2} - \frac{f-1}{2}\dot{\omega}_{dist}\left(\frac{\Delta t_{fire}}{2}\right)^2$$

$$\omega_{\lim} = \frac{f-1}{2}\dot{\omega}_{dist}\Delta t_{fire}$$

where:

ω_{lim} = maximum angular velocity

2.3.4.8 Measurement Process

A key aspect of Primary Mirror control is the process of measuring the relative positions of the various mirror segments. Selecting the measurement process will be done in the next phase, but many alternatives exist. Coarse measurements are needed for reinitialization after stationkeeping. Three candidate options have been identified:

Option 1 – Use a measurement laser shining on corner cube reflectors
Option 2 – Use a laser ranging imager, such as the one developed by Optech
Option 3 – Use the James Webb Space Telescope (JWST) approach of using an off-axis star and locating the image from each Primary Mirror segment

Fine measurements are needed continuously during observations for active mirror segment control. Laser ranging is probably not sufficiently accurate, but several options have also identified that could achieve sufficient accuracy:

Option 1 – Use a continuous adaptation of JWST approach that involves using off-axis stars
Option 2 – Use 1 or 2 calibration lasers on the Earth
Option 3 – Use an artificial star at the center of curvature of the Primary Mirror
Option 4 – Use image quality itself to identify mirror segments that need control

Fine measurements will generally need to be made while the telescope is imaging, which implies the need to perform measurements in a narrow optical band that is filtered out of the telescope image to avoid degradation due to stray light.

2.3.4.9 Control Authority (Primary Mirror Segments)

The Mirror Movers will hold the wire loop at the center of the Mirror Segments and use electric propulsion for coarse telescope pointing. A maximum force of 0.5 N is sufficient for electric propulsion to be used for coarse maneuvers. Magnetic forces will be used for initial alignment and to minimize tip-off rates when the Mirror Movers release the Mirror Segments. Laser forces will provide fine control of the Mirror Segments during telescope data collection. A minimum impulse of 6.7E-10 N is sufficiently small for the laser to be used for fine pointing. Additionally, all three of these control sources have been sized to overlap for smooth transitions (See Table 7).

Source of force	Min force (N)	Max force (N)
Electric Propulsion	5.0E-6	5.0 E-1
Magnetic force (at 1 cm)	5.1E-8	3.7 E-4
Magnetic force (at 10 cm)	1.3E-9	9.5 E-6
Laser force	6.7E-10	6.7 E-6

Table 7. Control Forces

Magnetic and laser force assumptions are listed in Table 8.

Force Type	Parameter	Coil on Mirror Segment powered by laser on a solar cell	Coil(s) on Mirror Mover
Magnetic	Current (mA)	0.1	1 to 250
	Number of windings	100	100 to 2000
	Radius (cm)	2	5 to 6
	Height (mm)	2	5 to 10
Laser	Min / Average / Max Power (w)	0.1 / 10 / 1,000	

Table 8. Magnetic and Laser Force Assumptions

2.3.5 Operations

2.3.5.1 Normal Operations

The Mirror Segment position and orientation is controlled entirely by light pressure from control lasers acting against control tabs on the perimeter of each of the mirror segments. Control forces and torques are available in all 3 axes in both directions and with redundancy and are very small, very well known, and easy to control. The Control Lasers are capable of controlling force continuously variable from 50 picoN to 5 microN.

2.3.5.2 Initialization/Stationkeeping

The system as a whole drifts N/S by up to 2 km/day, which must be corrected by regular stationkeeping maneuvers. The time required to perform the stationkeeping maneuvers is estimated to be 6 to 8 hours, if done daily (maneuver plus realignment) and 10 to 12 hours, if done weekly. The Primary Mirror segments are held by Mirror Movers (up to 7 segments per mover). Electric propulsion thrusters that have a maximum acceleration of about 5 micro-g's push all elements in the system. The entire system moves together (but not optically aligned), and the main mirror remains shaded during the operation. At the end of stationkeeping, the Mirror Movers provide coarse alignment and a corrected tip-off rate to improve alignment. They then move a few cm away from the mirrors. Magnetic interaction with the Mirror Mover is used to bring the mirror segment relative rates to near zero; all magnetic interaction is eliminated at the end of initialization.

2.3.5.3 Repointing

The in-focus area is an approximate 20 km diameter circle on the Earth (25 cm diameter circle at the focal plane). The area can be filled with pixels or the FPA can be moved as needed. Pointing the telescope at a new target area on the Earth visible from that location in GEO is done entirely by moving and reorienting the secondary mirror. The Primary Mirror and FPA can remain fixed (FPA tilts to point at the secondary). This technique allows rapid tracking or retargeting as needed, without system reinitialization.

2.3.5.4 Operational Modes

Four operational modes have been identified as follows:

a. Staring – observe a single area up to 20 km diameter at a 30 Hz frame rate;

b. Scanning – scan, for example, the east coast of the US in 20 km frames at 30 Hz;

c. Tracking – track LEO spacecraft, planes, planes, ships, or trucks over whatever distance cloud cover and the view from GEO allows;

d. Mapping – map a region in 20 km segments at a 30 Hz rate.

Operational limitations will be set largely by the number of arrays in the focal plane and the data rate required to bring images or results to the ground.

2.4 Task 4. Technology Roadmap

The Structureless Space Telescope is remarkably flexible, since steering, tracking, and repointing are done entirely with the secondary mirror. Further, the telescope optical properties can be changed on orbit by reconfiguring the primary mirror or moving the secondary mirror. The design is inherently robust and repairable, since most of the elements are replicated many times, and most components can be replaced on orbit. In fact, spares can be stored on-orbit or launched as part of any other GEO mission. The SST is also compatible with technology advances, so that new technologies can easily be introduced. Launch costs can be a small fraction of Hubble repair missions because of the relatively small overall mass of the system and the fact that replacement parts are relatively small and can be launched by many existing or future launch vehicles. If multiple telescopes are placed in GEO for global monitoring, elements can be interchanged among them. The total amortized cost of 1-m data from GEO can be less than 10¢ per frame, with substantial potential for going lower

Table 9 lists issues or problem areas and candidate ways to reduce the risk or eliminate the problem. In effect, this table also provides a lead into the roadmap for future work on the SST.

Issue or Problem Area	Risk Retirement Strategy
Optical Design/Optical Margins	1. High fidelity optical simulation 2. Ground demo in air 3. Ground demo in vacuum
Orbit/Attitude Control (fine and coarse), including measurement process	1. Analysis a. Detailed control system analysis b. High fidelity coupled orbit/attitude simulation c. System level review meeting 2. Test and Demonstration a. Ground testing (1-D, 2-D subscale in air, then in vacuum) b. LEO subscale demonstration c. GEO demonstration, if needed
Hidden "show stoppers" or items which strongly drive cost, risk, or performance	1. Detailed system design and configuration 2. Point design with GSFC IMDC 3. Systems engineering evaluation/resolution of identified problems 4. Broadly attended system level review
Design & manufacture of mirror segments (principal mass and cost driver)	1. Detailed design and manufacturability assessment by Kodak or Goodrich 2. Manufacture of a subscale or full scale segment
Laser pointing and control	1. Evaluation of in-space and proposed laser systems 2. Detailed system design and review 3. Build test unit for ground or on-orbit demo, if needed
Mirror Mover design, motion, and control of mirror segment	1. Detailed system design 2. Ground test as part of control system testing above 3. On-orbit demonstration, if needed (part of LEO or GEO demo)
Overall System Performance – Will it work?	1. 20% of full scale 2-dimensional ground demonstration of end-to-end system performance

Table 9. Risk Retirement Strategy

Microcosm has had discussions/meetings with Kodak, Goodrich, Los Alamos National Laboratory, and Goddard Space Flight Center Integrated Mission Design Center to determine how to proceed. The overall path is to start with additional studies, followed by successively more complex simulations and hardware experiments that could lead to potential on-orbit implementation in approximately 10–12 years, if the process goes smoothly. The immediate next step would be 6–9 month systems study $400K (the NIAC Phase 2), with substantial ground-based testing for total cost of $2M–$3M afterwards. The first stage to achieve the ground-based testing has three major elements:

1. High fidelity system modeling -- both optics and coupled orbit/attitude
2. Detailed system design – make use of Goddard Space Flight Center Integrated Mission Design Center
3. Begin ground test program
    a. Optical performance and margins
    b. Measurement and control system performance and dynamic range

2.5 Task 5. Project Management/Documentation

Technical interchanges took place to incorporate final inputs from the subcontractors, along with reviews of this document during its preparation.

3 Future Plans

The next step is to prepare a Phase 2 proposal that will be submitted at the same time as this report.

4 Conclusions

The SST is remarkably flexible, in particular because steering, tracking, and repointing is done entirely with the secondary mirror. In addition, the telescope optical properties can be changed on orbit by reconfiguring the primary mirror or using new secondary mirrors. If desired, different FPAs in different focal planes can be used. The system is also inherently robust and repairable, and most components can be replaced on orbit. It is also possible to have spares on orbit or launched as part of any other GEO mission (which is a cost reduction factor). Further, the SST is compatible with technology advances, and new technologies easily introduced. The overall system launch mass is such that initial launch costs will be a small fraction of Hubble repair missions. If multiple telescopes are placed in GEO for global monitoring, elements can be interchanged among them, which adds another layer of savings due to the interchangeability capability. Finally, the total amortized cost of 1-m data from GEO can be less than 10¢ per frame, with substantial potential for going lower.