NIAC Phase I Final Presentation

Structureless Space Telescope (SST):

A New Class of Space Observatory

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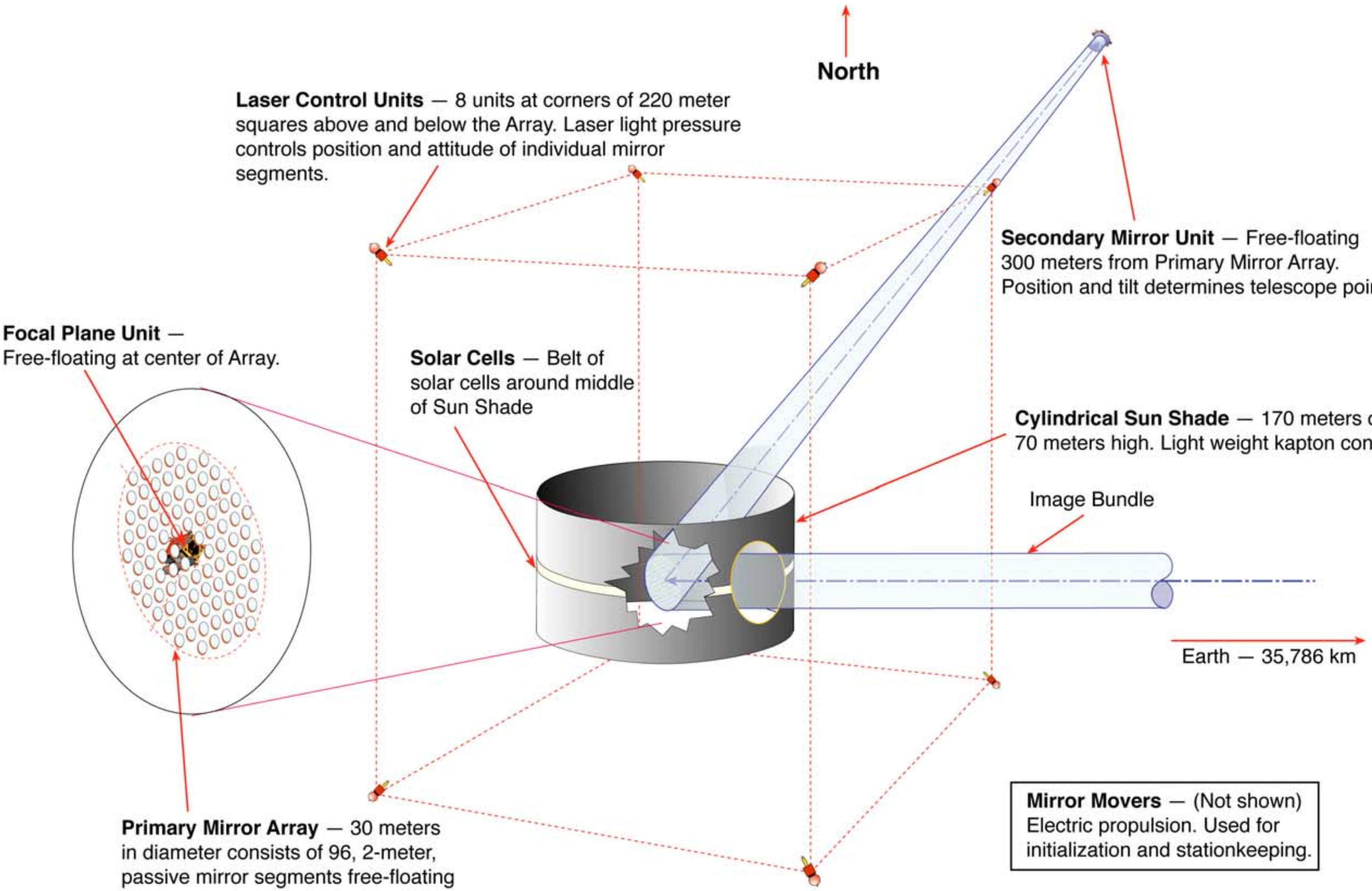
Structureless Space Telescope: 1-m Continuous Observation from GEO



Laser Control Units — 8 units at corners of 220 meter squares above and below the Array. Laser light pressure controls position and attitude of individual mirror segments.

Secondary Mirror Unit — Free-floating 300 meters from Primary Mirror Array. Position and tilt determines telescope pointing.

Focal Plane Unit — Free-floating at center of Array.

Solar Cells — Belt of solar cells around middle of Sun Shade

Cylindrical Sun Shade — 170 meters diameter, 70 meters high. Light weight kapton construction.

Primary Mirror Array — 30 meters in diameter consists of 96, 2-meter, passive mirror segments free-floating at center of Sun Shade. Fixed pointing 26.6 degrees from horizontal.

Mirror Movers — (Not shown) Electric propulsion. Used for initialization and stationkeeping.

Executive Summary

- Concept of large space telescope made of independent mirror segments has been around for many years
  - Problem is made workable by using free-floating passive mirror segments controlled by light pressure from near-by control lasers
- Phase I focused on an Earth-observation system at GEO
  - Phase II effort will examine a Lagrange Point outward looking system
- Preliminary GEO system parameters

Resolution	1 m at nadir over 20 km FOV
Frame rate	~30 frames/sec
Total on-orbit mass:	~ 5,000 kg
Total power (operating and stationkeeping)	32 kW
Total cost [NRE, on-orbit validation ($150M), build, launch, ground segment, and 1 year of operations]	$1.2 Billion

  - These are preliminary results based on a multi-year IR&D effort and a $75K NIAC study -- not definitive, but no show stoppers found to date and many alternatives exist for most elements
- Steering the field-of-view done entirely by moving and tilting the secondary mirror
  - Allows tracking of rapidly moving objects or events on Earth or in near-Earth space
- All reflective optics allows operation at any wavelength of interest

Although additional systems engineering is necessary, preliminary results show a truly transformational capability with no technology breakthroughs required.

What Makes it Work?

- How is this approach different from prior free-floating segmented mirror designs?
  - Four elements have changed

1. Primary mirror segments controlled by forces applied from outside the segments
   - Mirror elements are passive and are controlled operationally by light pressure from lasers external to the mirrors themselves
     - In prior designs, each segment was a miniature spacecraft with its own propulsion, control, and other subsystems -- complex and hard to get ultra-fine control
     - Lasers provide continuously variable forces and torques in all 3 axes from 50 picoN to 5 microN, i.e., remarkably small, yet very well known and very controllable
   - Each segment is controlled independently of the others
2. “Mirror movers” used for stationkeeping and initialization
   - Use small magnetic forces and electric propulsion to “grab” mirrors and move them
   - Highest acceleration mirrors ever see on orbit is ~5 micro-g’s during stationkeeping
3. “Tilted and rotating” primary mirror allows all mirror segments to be in Keplerian orbits
   - Don’t need continuous force application to keep segments in a non-Keplerian orbit
4. All pointing done by moving and tilting the secondary mirror
   - Capability based largely on current work on liquid metal mirrors (i.e,. rotating mercury mirrors)
   - Don’t have to realign or reinitialize the primary to change where the telescope is looking
   - Allows rapid scanning, tracking, or repointing to a target of opportunity

System requires development and lots of systems engineering, but no technology breakthroughs.

Introduction to Microcosm

- Microcosm is a 20 year old small business located in El Segundo, CA
- Microcosm has recognized expertise in space mission engineering, combined orbit and attitude control systems, and constellation management, and is widely known due to the success of its technical publications
  - — *Space Mission Analysis and Design*
  - — *Reducing Space Mission Cost*
  - — *Spacecraft Attitude Determination and Control*
  - — *Spacecraft Orbit and Attitude Systems*
- These "corporate brochures" highlight Microcosm's engineering expertise in the areas of mission and systems engineering and autonomous GN&C system development
- Microcosm has previously developed a number of innovative technologies
  - — Developed and flew the first ever fully autonomous on-board orbit control (OCK, flown on UoSAT-12 in 1999)
  - — Developed and flew the first ever fully autonomous navigation system (MANS, flown on TAOS in 1994)
  - — Scorpius® ultra-low cost launch system
    - Example: 700 lbs to LEO for < $3 million
- Extensive experience in the design, modeling, and analysis of mission solutions for constellation management, satellite formations, and rendezvous and docking

The thrust of our activity is twofold -- creating truly transformational systems and technologies, and reducing space mission cost.

Introduction to Michigan Aerospace Corporation (MAC)

- Formed in 1996 to commercialize several unique spacecraft and aircraft technologies
- Areas of expertise relevant to Structureless Space Telescope project
  - Optical analysis, design, and testing
  - Atmospheric modeling
  - Custom detector design and fabrication
  - Signal and image processing, real time systems
  - Hardening for space systems and other harsh environments
- Space instruments designed and built by MAC
  - Visual Airglow Experiment flown on Atmospheric Explorer -C, -D, and -E
  - Fabry-Perot interferometer and star tracker on Dynamics Explorer-2
  - High Resolution Doppler Imager (HRDI) flown on UARS
  - Robotic Material Processing System flown on STS-64
  - Automated Wafer Cartridge System intended for Wakeshield Facility
  - Autonomous Rendezvous and Docking mechanism intended for the Commercial Experimenter Transporter
  - Propulsive Small Expendable Deployer System (ProSEDS)

Microcosm and MAC have an extensive history of cooperation on multiple projects. The two organizations can work together as a fully integrated team.

Structureless Space Telescope Operations Summary

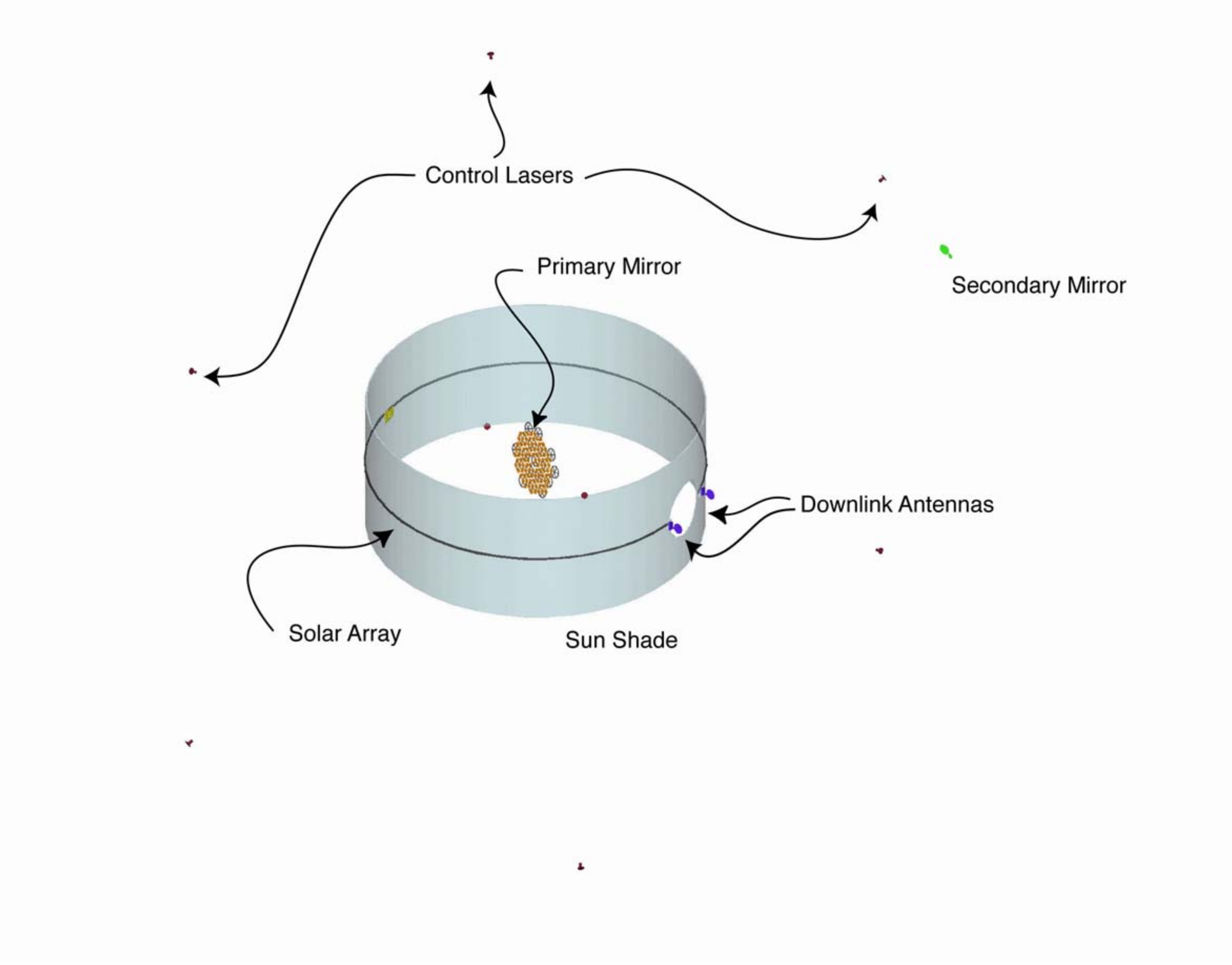
- <u>Normal Operations</u>
  - Mirror segment position and orientation controlled entirely by light pressure from control lasers acting against control tabs on the perimeter of the mirror segments
    - Control forces and torques available in all 3 axes in both directions with redundancy
    - Control forces very small, very well known, and easy to control
    - Laser control force continuously variable from 50 picoN to 5 microN (5 orders of magnitude)
  - Data collected at approximately 30 Hz frame rate

- <u>Initialization/Stationkeeping</u>
  - System as a whole drifts N/S by up to 2 km/day
  - Corrected by regular stationkeeping maneuvers
    - 6 to 8 hours if done daily (maneuver plus realignment)
    - 10 to 12 hours if done weekly
    - Primary mirror segments held by mirror movers (up to 7 mirror segments per mover)
    - All elements pushed by electric propulsion thrusters
      - Maximum acceleration ~5 micro-g's
      - System moves together (but not optically aligned) and main mirror remains shaded
    - At end of stationkeeping, mirror movers provide coarse alignment, corrected tip-off rate to improve alignment, and then move a few cm away from the mirrors
  - Magnetic interaction with mirror mover used to bring mirror segment relative rates to near zero; all magnetic interaction eliminated at end of initialization

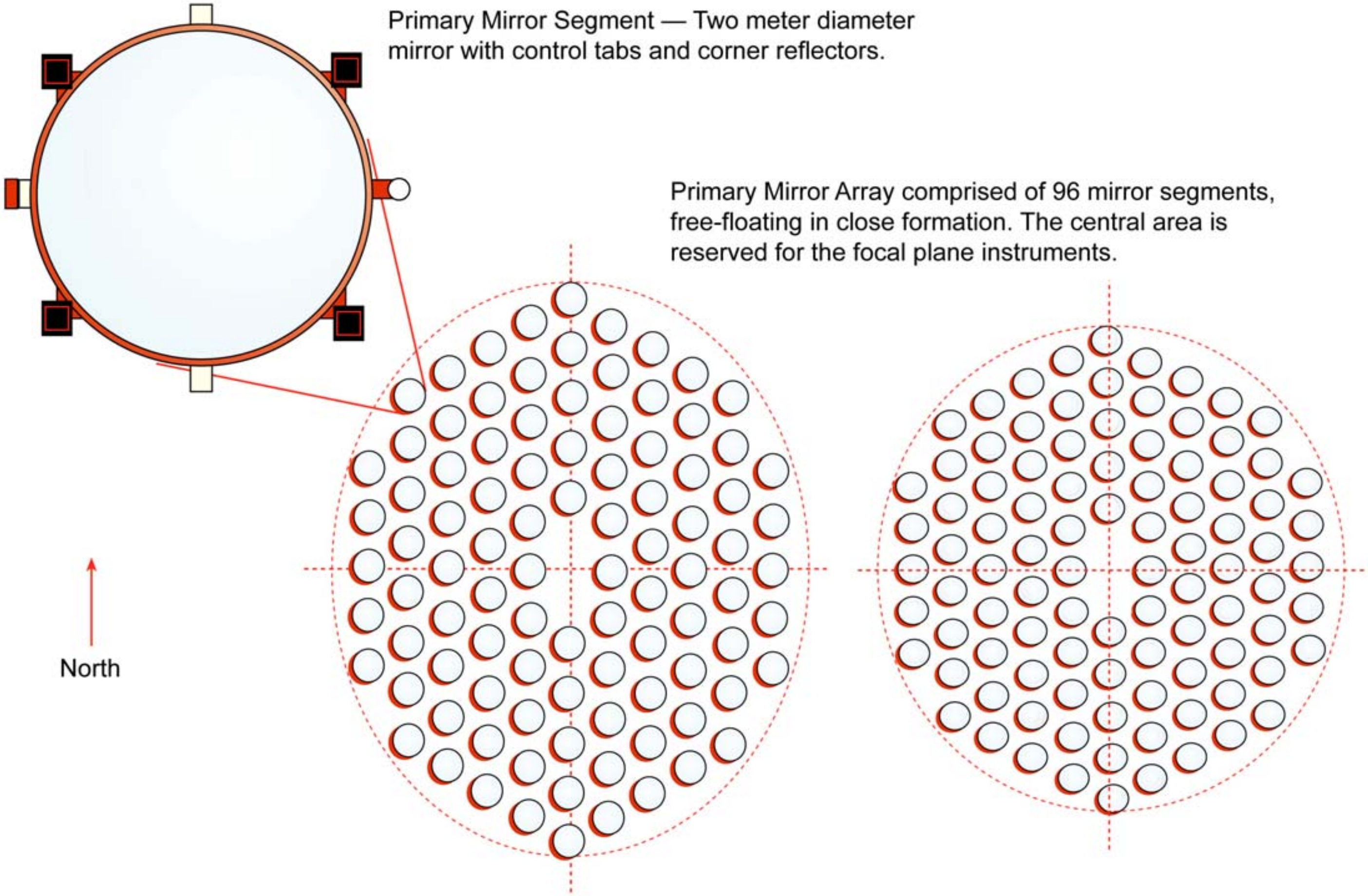
Operations Summary (continued)

- Repointing
  - In focus area is an ~20 km radius circle on the Earth (25 cm diameter circle at the focal plane)
    - Can fill the area with pixels or move the FPA as needed
  - Pointing 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
    - Primary mirror and FPA can remain fixed (FPA tilts to points at secondary)
    - Allows rapid tracking or retargeting as needed, without system reinitialization
- Operational Modes
  - Staring
    - Watch a single area up to 20 km diameter at 30 Hz frame rate
  - Scanning
    - Can scan, for example, east coast of the US in 20 km frames at 30 Hz
  - Tracking
    - Can track LEO spacecraft, planes, ships, or trucks over whatever distance cloud cover and the view from GEO allows
  - Mapping
    - Can map a region in 20 km segments at 30 Hz rate

SST System Architecture



Segment Layout

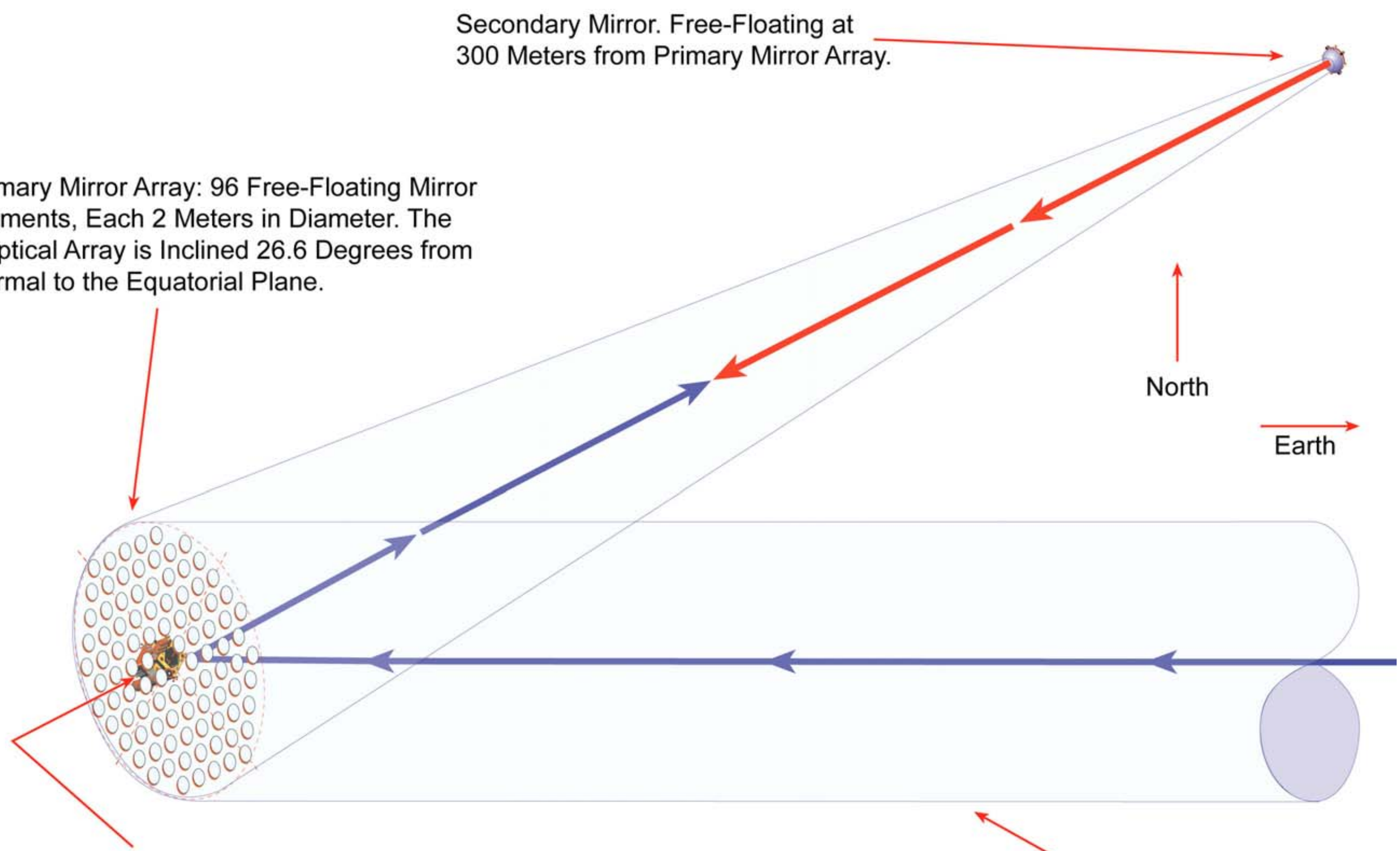


Primary Mirror Segment — Two meter diameter mirror with control tabs and corner reflectors.

Primary Mirror Array comprised of 96 mirror segments, free-floating in close formation. The central area is reserved for the focal plane instruments.

Primary Mirror Array seen normal to its plane is an ellipse with short axis parallel to equator.

Primary Mirror Array lifted 26.6 degrees to the North appears as a 30 meter circular mirror from Earth.



Secondary Mirror. Free-Floating at 300 Meters from Primary Mirror Array.

Primary Mirror Array: 96 Free-Floating Mirror Elements, Each 2 Meters in Diameter. The Elliptical Array is Inclined 26.6 Degrees from Normal to the Equatorial Plane.

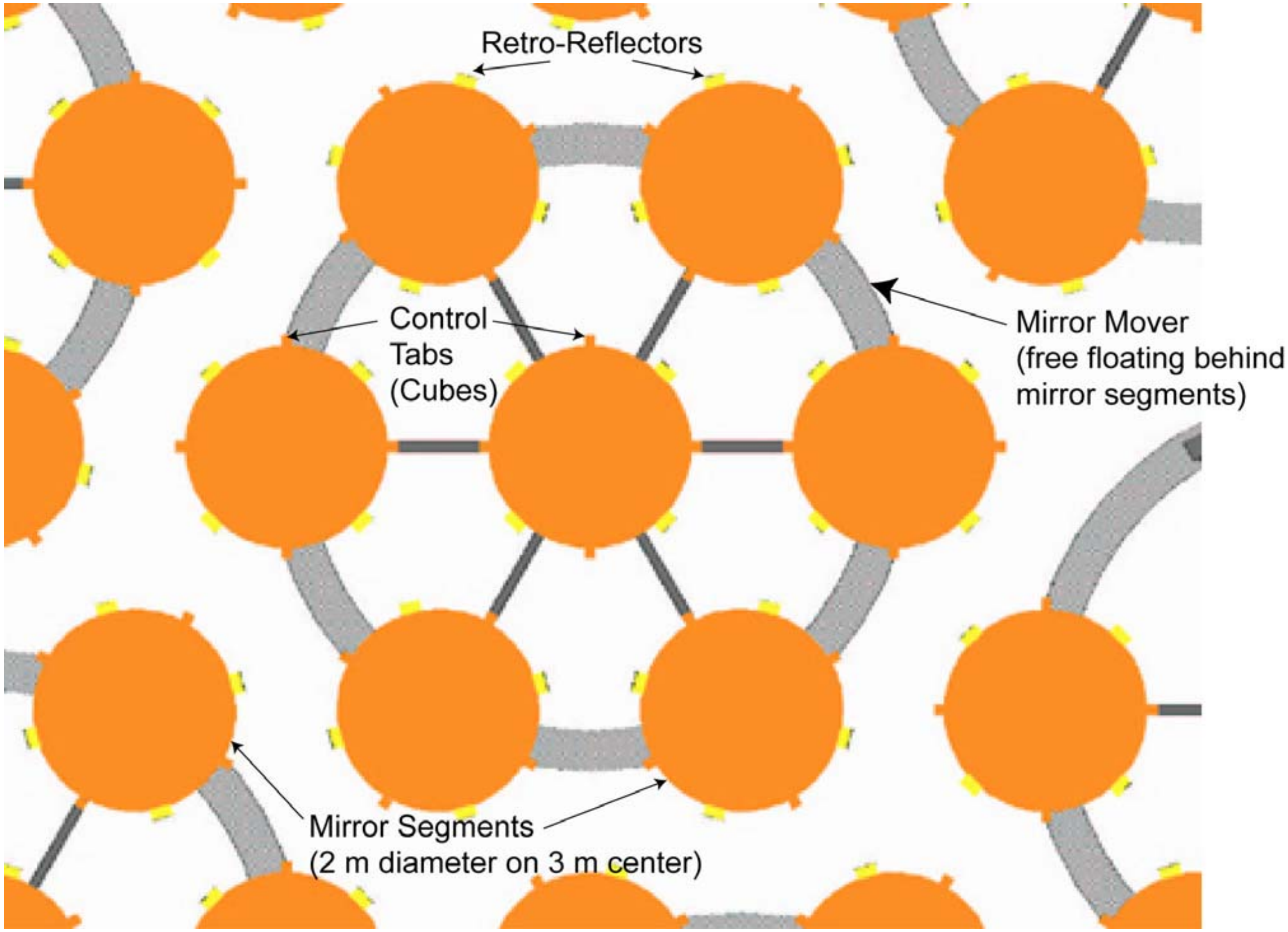
North

Earth

Focal Plane Unit with Science Instruments. Free-Floating at or Behind the Center of the Primary Mirror Array.

30 Meter Image Bundle

on Primary Mirror Segments



Primary Mirror

- Primary mirror baseline configuration consists of 96 2-m diameter passive round mirror segments
  - 3-m center-to-center hexagonal pattern
  - Tilted 26.6 deg relative to the horizontal
- Purely passive segments, no electronics or controls
  - Tabs on edges for control and measurement laser
  - Steel wire loop near center for magnetic hold
  - Set of current loops, powered by laser illumination on a solar cell, provide for magnetic control that can be turned on and off, push or pull
- Mass estimate = 9.4 kg/segment
  - Launch loads distributed over entire surface
- Highest on-orbit acceleration ~5 micro-g's
- Optical surface is spherical with ~630 m radius
  - Deviation from flatness of < 1 mm over mirror surface
- After initial set-up, mirror is shaded at all times (operations and stationkeeping) and has a temperature of ~ 40°K
- Structure of the primary mirror can be changed or expanded by moving or adding mirror segments
  - Provides unique operational flexibility

- 300 m in front of and above primary mirror (not in incoming light path)
- 2 m to 3 m radius, figure not yet set
- 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 approximately 80 m diameter circle provides repointing, scanning, mapping, and tracking
- Nominal position is 240 m above the orbit plane and 180 m in front of the primary
  - — Implies secondary mirror is in a non-Keplerian, non-geostationary orbit and will require continuous force application to maintain its orientation
  - — Force to maintain position = 0.0023 mN/kg = 0.069 mN for 30 kg secondary
    - Easily done with electric propulsion
    - Plume flows down and away from the primary mirror
    - Can be split into 2 parts so as not to go through the optical line of sight
- Unlike the primary mirror, the secondary mirror is an active component with continuous, low-level force required and the need to move and tilt with respect to the primary during mission operations

Depending on the angular size of the region to be scanned without moving the primary, it may be necessary to add a tertiary mirror and move the FPA.

- Mirror Movers
  - During normal operations, movers play no part in telescope control and remain a few cm behind the mirror segments -- no strong requirements during this mode
  - For stationkeeping or initialization, each mover can hold, move, and release up to 7 mirror segments
  - Each mover uses a set of small current loops with continuous current control to provide controlled release and tip-off with controlled magnetic “action at a distance”
  - Uses electric propulsion for stationkeeping with maximum acceleration of ~5 micro-g’s
- Control lasers
  - Provide continuous fine control of primary mirror segments during operations
  - Arranged on corners of two squares above and below primary mirror
    - Could be free-flyers or attached to Sun shade
    - Control requirements on laser position and pointing are only moderate
  - Laser beam can hit 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
- Measurement Lasers
  - Used in coarse mode for measuring positions for initialization and stationkeeping
  - Insufficient accuracy for measurement during operations
    - Higher accuracy options exist for operational mode

(continued)

- Sun shade
  - — Maintains primary mirror, Focal Plane Units, and mirror movers in continuous shade
  - — Very modest position, attitude, and structure requirements
  - — Initial design is a “tuna can” 170 m in diameter and 70 m high
  - — Open on top and bottom with aperture hole facing viewing direction
  - — May choose to incorporate solar cells and System Bus Unit into the Sun shade structure
- Focal Plane Unit (FPU)
  - — Free-flyer at or near the center of the primary mirror -- can be multiple FPUs for a single secondary
    - Primary and secondary optics are both reflectors, so FPUs can work at any desired wavelength
  - — Image brightness should allow frame rate of approximately 30 Hz in most cases
  - — In-focus region will be a circle approximately 25 cm in diameter
    - Allows many arrays to be incorporated in a single focal plane unit
  - — FPUs with multiple arrays and 30 Hz frame rate implies potential for very high data rates
  - — Data sent to System Bus Unit for processing and transmission to ground

A large number of independent Focal Plane Units can be used. They can be interchanged in position or the secondary mirror can be tilted so as to move quickly from one FPU to another.

(continued)

- System Bus Unit
  - Provides basic services for the system -- power, command and telemetry, central computing and decision making, inertial orbit and attitude
  - May be integral with Sun shade or a separate unit
  - On-orbit processing, data compression, and telemetry may be major issues because of the potential for truly enormous throughput
- Power Transmission
  - Mirror movers need power, but are continuously shaded
  - Preliminary solution is to use microwave power transmission
    - Solar cells conveniently placed on outside of Sun shade with power transmitters on the inner side of the Sun shade
    - Rectennas located on whatever equipment needs power
    - Overall transmission efficiency initially taken as 60%
- Rovers
  - Monitoring robots basically similar to MIT Spheres mini-spacecraft
  - Used for inspection and problem solving, e.g., removal of a defective unit
  - Includes thermal sensor, visual camera, and laser 3-D sensor, such as the unit built by Optech
  - Includes manipulator hand which allows it to grab other elements as needed
  - Use very small cold gas thrusters for faster motion than other elements
  - Normally docked on bus unit or Sun shade

- Optical design is challenging in that it requires control of mirror segments to approximately 50 nm in position and 50 nrad (0.01 arc sec) in angle
  - — Both measurement and control issues discussed separately
- System goal is to achieve 60% to 70% of diffraction limited performance
  - — Critical to allow margin so system doesn't need to be perfect
  - — Diffraction limit at nadir is ~0.7 m on the ground
  - — General agreement that goal can be achieved given that measurement and control problems are workable
- Most challenging aspect is broad range of off-axis performance
  - — Would like to work 8 deg off of nadir to reach 25 deg elevation angle on the Earth
    - Fall-back position would be to limit viewing to, for example, North America and move the main mirror (~ 4 hours) to view South America
  - — This goal is consistent with work currently being done on liquid metal (LM), typically mercury, mirrors
    - LM mirror is formed by equilibrium position of a rotating fluid sitting horizontally -- needs large off-axis coverage to get a reasonable view of the sky
  - — Much of the work is currently being done at U. of Arizona and INO in Canada
  - — Conversations with the experts in the field (S. Thibault, E. Borra) by MAC optical designers indicate that the objective can be achieved over the full range

A key issue for follow-on work will be a detailed optical design, coupled with detailed modeling of the orbit and attitude. Optics are challenging, but workable, with strong fall-back options if margins become too tight.

Large Scale

- The telescope motion is most easily thought of as the sum of large scale motions which 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
- Large scale motion
  - The whole telescope is in a nearly circular, near 0 inclination, geosynchronous orbit moving at 3.075 km/sec in inertial space
    - The degree to which the fundamental orbit is not circular or not 0 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 ~2 km/day
    - Causes a need for regular stationkeeping, but does not disrupt telescope structure
    - 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 Sun shade
  - Must be accounted for in the motion of the secondary mirror, Sun shade, and control lasers

Small Scale

- 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
  - 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 effect 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
  - Differences in orbital elements require continuous stationkeeping on the secondary mirror that is in a non-Keplerian orbit
    - Accommodated in the secondary mirror control budget
- Solar/lunar tidal forces
  - These very small differential forces 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 (detailed force and torque budget available)

Requirements during Operations Mode

	Dominant	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.							
		* Fine measurements done by analysis of the image							

- Control requirements on most components are modest
  - — Comes about largely because most components are not a part of the optical path and have no direct connection to the optical components
    - Allows substantially less stringent requirements than for most telescopes
- 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 shows very low frequency requirement on mirror segment attitude motion -- implies works well with laser control of multiple elements

- 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 measurement needed for reinitialization after stationkeeping
  - Option 1 -- use a measurement laser shining on corner cube reflectors
  - Option 2 -- use a laser ranging imager, such as the one built by Optech
  - Option 3 -- use James Webb Space Telescope (JWST) approach of using an off-axis star and locating the image from each primary mirror segment
- Fine measurement needed continuously during observations for active mirror segment control
  - Laser ranging is probably not sufficiently accurate
  - Option 1 -- Use continuous adaptation of JWST approach of using off-axis stars
  - Option 2 -- Use 1 or 2 calibration lasers on the Earth
  - Option 3 -- Use 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
  - Implies need to do measurement in a narrow optical band that is filtered out of the telescope image to avoid degradation due to stray light

Both Feasible and Practical?

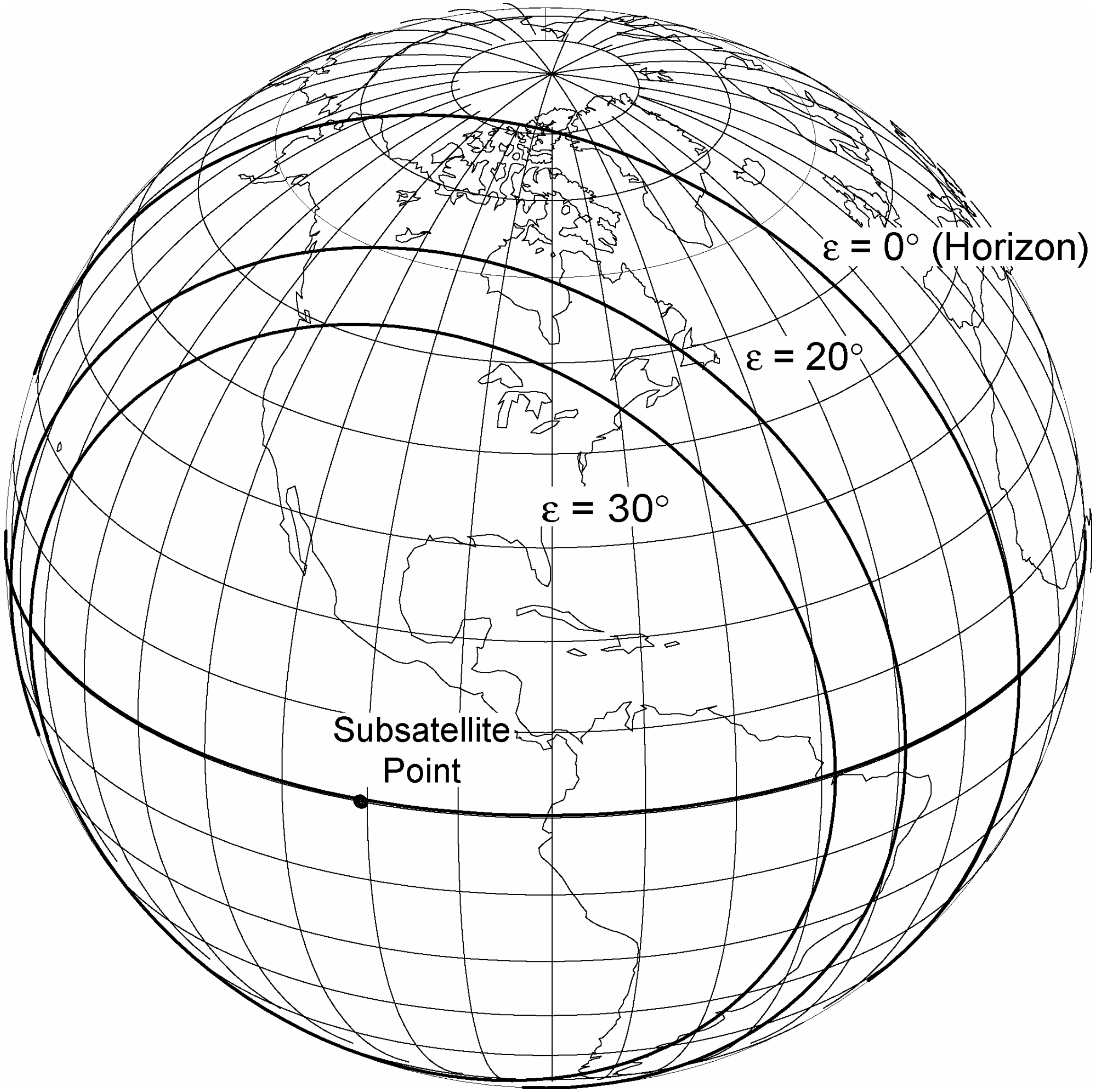
- A great deal of systems engineering still needs to be done
  - There may yet be elements that make the system unworkable, require new technology, or make it too expensive -- but we haven't found them
- There are strong arguments for system feasibility
  - Nearly all components are in Keplerian orbits
    - Makes disturbance forces very small away from low planetary orbits
  - Laser control, magnetic control, and electric propulsion provide continuous range of control forces from 1 nanoN to 100 mN
    - Have active control in all 3 axes -- both forces and torques
  - Maximum telescope acceleration is less than 10 micro-g's during stationkeeping
  - Repointing and steering can be done entirely by motion of the secondary mirror
    - Makes tracking, mapping, and retargeting much easier and very rapid
    - Ability based on current work on liquid mirror telescopes
  - Optical design is challenging, but robust
    - Only tight requirement on mirror segment control is on roll and pitch attitude and radial position
  - High level of redundancy in all key elements
  - Most elements easily replaced on orbit
  - No technical breakthroughs required

The Structureless Space Telescope replaces mechanical structure with control and processing, which provides a whole new regime of flexibility, reconfigurability, and expandability.

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 seg-ments (principal mass and cost driver)	1. Detailed design and manufacturability assessment by optics house 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

- Values of ε are the elevation angles as seen from the ground.

- The limits of good coverage would typically be between 20 deg and 30 deg in elevation angle.



SST Weight/Power/Cost Budgets Round 1.3 1/26/04

Number	Component	Mass (kg)	Power (W)	Tot Mass (kg)	Operating Tot Power (W)	Statnkping Tot Power (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

(part 2)

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	620.256148	825	620.256148	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**
		(kg)		**(kg)**	**(W)**	**(W)**

		Round 1.3	1/26/04		Learning Curv	90%			
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	

- Have used Unmanned Spacecraft Cost Model (USCM) from SMAD III for most cost elements (NRE and TFU costs)
  - Assigned increased cost to many components for increased development
  - Used 90% learning curve for multiple units
- Weight, power, and cost driven largely by the mass of the primary mirror segments
  - Determines the size of the laser control units which are the principal elements of mass and power
  - Implies need to look very closely at the manufacturing of the mirror segments during next study phase
    - Can be fully supported over entire surface area during launch
    - The largest acceleration they will see on orbit is less than 10 micro-g's
- Cost includes NRE, ground and on-orbit development tests, manufacturing, launch, deployment, ground segment, and 1 year of operations (50 people)
  - Does not include applications planning or data reduction and analysis
- <u>Recall that cost depends on how it is built, rather than what is built</u>
  - The way the program is run will be the dominant cost driver
- Microcosm's main business area is reducing mission cost
  - We have not tried to do that here, in order to obtain a conservative cost estimate

The Lagrange Point Observatory

- Work to date has concentrated on a GEO Earth observation system because that was the most challenging
  - "Large" disturbance forces and torques
  - Large field of regard to cover with only secondary mirror motion
- Equally useful system would a Lagrange Point Observatory (LPO) looking outward
  - Terrestrial planet finder
  - Monitoring planets, asteroids, and comets in the Solar System
  - Searching for Kuiper Belt objects
  - Examination of nebulae, clusters, galaxies, and quasars at multiple wavelengths
- Will examine LPO during Phase II
  - Much smaller disturbance forces and torques allow a larger system with comparable or smaller mass
    - Mass budget dominated by laser and power systems, both of which depend on the size of the disturbances that must be overcome
  - Smaller disturbance budget may allow repointing of the primary mirror to examine different objects
    - Less need for rapid frame rate and more need for extended exposures using large light gathering power
  - Will trade off need for resolution vs. light gathering power in determining fill factor
    - May change fill factor depending on what is being observed

The LPO has higher resolution and light gathering power than current approaches. In addition, it has far more growth potential and exceptional flexibility. Example: we can dynamically change the mirror segment spacing for specific observations.

- The Structureless Space Telescope is remarkably flexible
  - Steering, tracking, repointing done entirely with the secondary mirror
  - Can use different FPAs in different focal planes, if desired
  - Telescope optical properties can be changed on orbit by reconfiguring the primary mirror or using new secondary mirrors
- The design is inherently robust and repairable
  - Most of the elements are replicated many times
  - Most components can be replaced on orbit
    - Can have spares on orbit or launched as part of any other GEO mission
- Compatible with technology advances
  - New technologies easily introduced
  - Launch costs can be a small fraction of Hubble repair missions
- If multiple telescopes are placed in GEO for global monitoring, elements can be interchanged among them
- Total amortized cost of 1-m data from GEO can be less than 10¢ per frame, with substantial potential for going lower

The Structureless Space Telescope has the potential for creating a dramatically expanded near-term capability in Earth observation and monitoring. Similar advances are expected for an outward looking, Lagrange Point Observatory.