RASC Space Theme 2: Science From New Perspectives

Earth Atmosphere Observatory at L2

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February 5, 2004

Background

-
  - Virtual Structure Gossamer Space Telescope (Edward Mettler – JPL)
  - Atmospheric Remote-Sensing Observatory at the L2 Lagrange point (Joseph Zawodny – LaRC)

- **Study Approach:**
  - The "Virtual Structure Gossamer Space Telescope" selection serves as the focal point while the "Atmospheric Remote-Sensing Observatory at the L2 Lagrange Point" selection provides the science requirement drivers

- **Objectives**
  - Develop a concept for an Earth observing capability at Earth-Sun L2
  - Define the science to be conducted and the associated instrumentation
  - Develop conceptual designs for the instrument, telescope, and supporting spacecraft
  - Define an end-to-end mission architecture
  - Assess the technical challenges and identify enabling technologies

Study Team Organization

LaRC Science

JPL Principal Architect

NASA Centers Technical Support

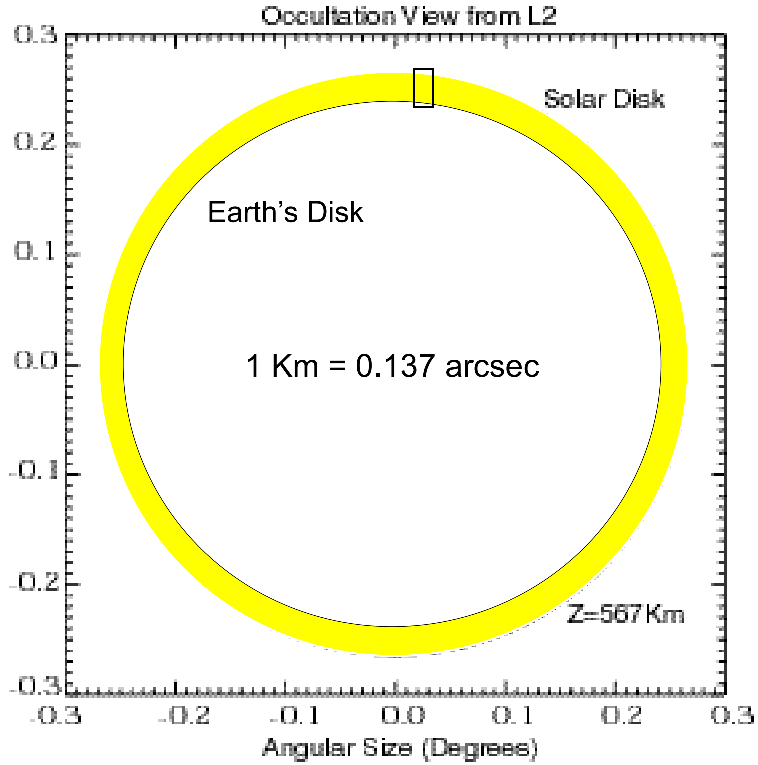
- LaRC
- GSFC
- GRC

Overall study integration was provided by Jeff Antol at LaRC. Technical Integration Support was provided by Dr. Ram Manvi of JPL .

Ed Mettler at JPL was the Principal Architect. He developed the Telescope Concept to meet the Science Requirements developed at LaRC by Dr. Joe Zawodney. A number of professionals from NASA Centers made significant technical contributions toward the ESL2 Telescope design

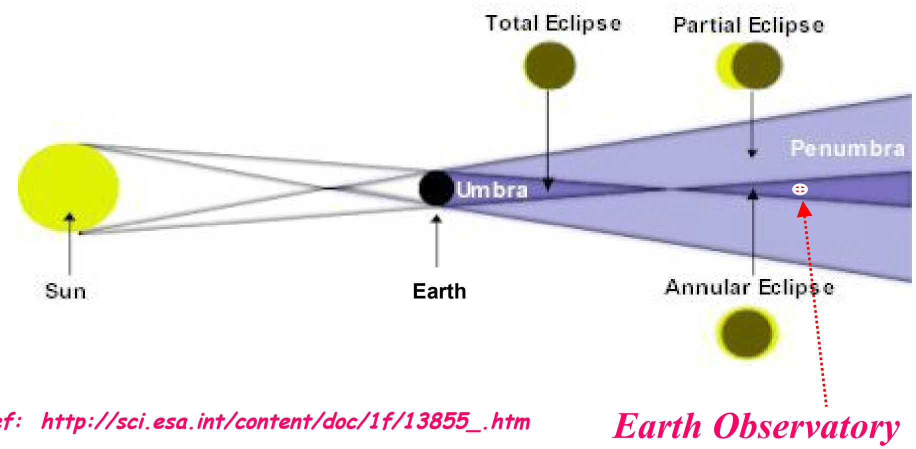
Science Objectives

- **Study Earth's atmosphere as it occults sunlight**
- **Solar Occultation Best Suited for Long-Term Climate Change Studies**
  - **Earth Sun L2 is the optimal place to deploy solar occultation instruments.**
  - **Hourly measurements at all latitudes**
  - **Global, high-resolution 3D maps of CO_2, O_3, O_2, CH_4, H_2O, N_2O**
  - **Can't be done continuously or globally from LEO**
- **Instruments include: Offner Imaging Spectrometers, Mid-IR & Gas Filter Correlation Radiometer (GFCR) Imager**
- **Observation Strategy:**
  - **Scan around the annular ring of the Earth's atmosphere at least 360 times per day for ~1° "longitudinal" sampling**
  - **Sample each rotation at least 360 times to provide ~1° "latitudinal" sampling**

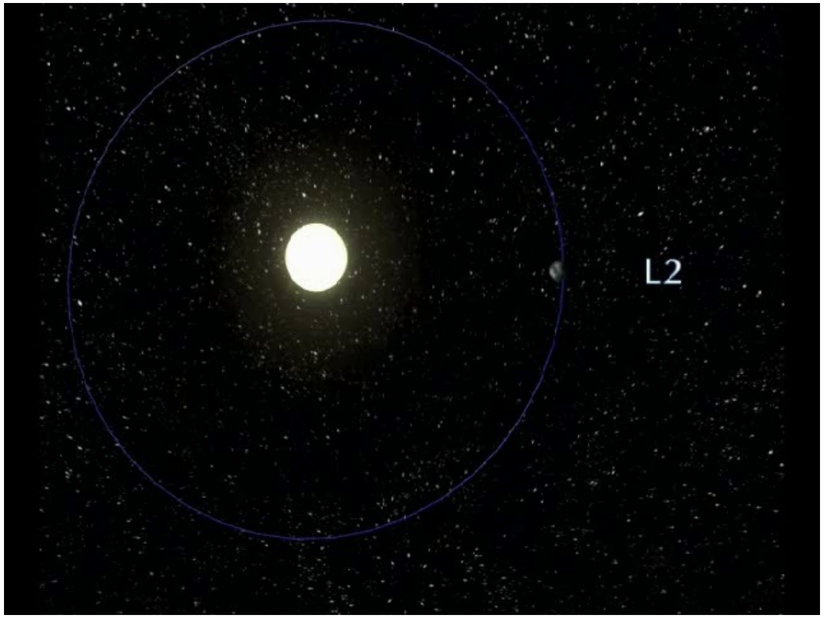


From L2 the Sun is slightly larger than the Earth and places the annular ring of the Earth's atmosphere into permanent occultation. Spatial sampling is limited only by the speed of the instruments and the down-link bandwidth.

Observatory Orbit



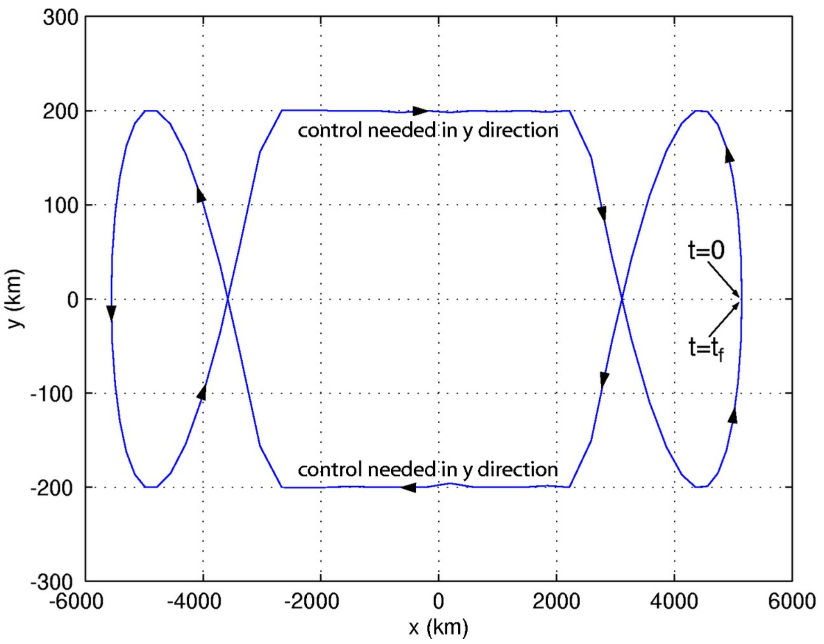
Ref: http://sci.esa.int/content/doc/1f/13855_.htm



- **Powered "orbit" near L2 to maintain observatory position within the annular eclipse**
  - **Must stay within 200 km of the Sun-Earth line**
- **"Standard" orbits won't work**
  - **Lissajous and halo orbits stray far from Sun-Earth line**
  - **Nearly rectilinear halo orbits are perpendicular to line between primaries, and don't account for 4th body perturbation**

Minimum Fuel Periodic Orbit at Earth Sun L_2

- **Must stay within 200 km of the Sun-Earth line, however, cyclic drift of +/- 5000 km *along* the Sun-Earth line is allowed to reduce propellant requirements**



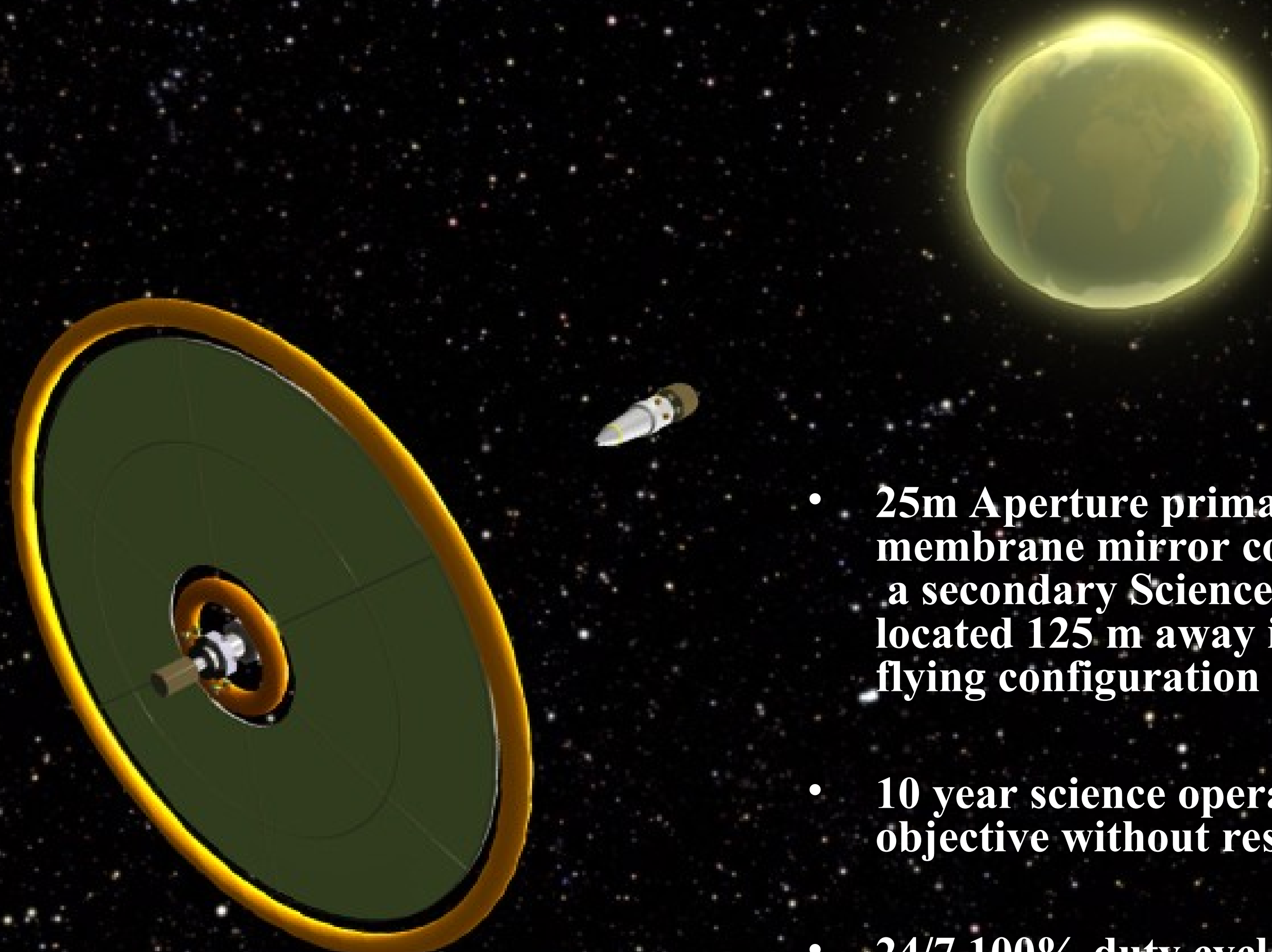
- **Without the "candy wrapper" orbit, a 10 year mission is not possible without the resupply of propellant**

- References:

Shen, H., Kumar, R. R., and Seywald, H., "Minimum-Fuel Periodic Orbits in the Vicinity of a Fixed Point on the Sun-Earth Line: The Planar Case," AAS 04-247, 14th AAS/AIAA Space Flight Mechanics Meeting, Maui, Hawaii, Feb. 8--12, 2004

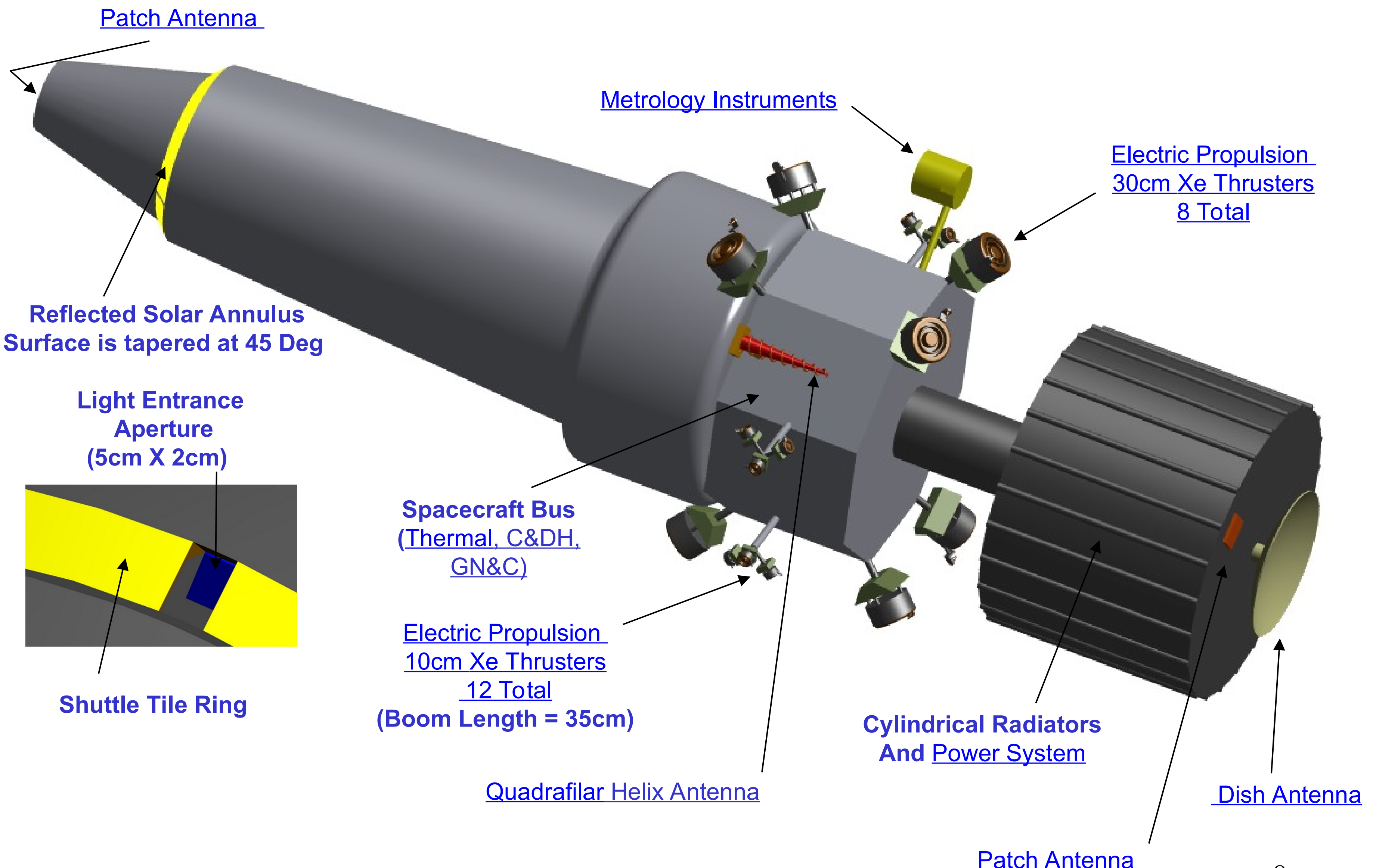
Roithmayr, C. M., and Kay-Bunnell, L., "Keeping a Spacecraft on the Sun-Earth Line," AAS 04-246, 14th AAS/AIAA Space Flight Mechanics Meeting, Maui, Hawaii, Feb. 8--12, 2004.

Observatory Architecture

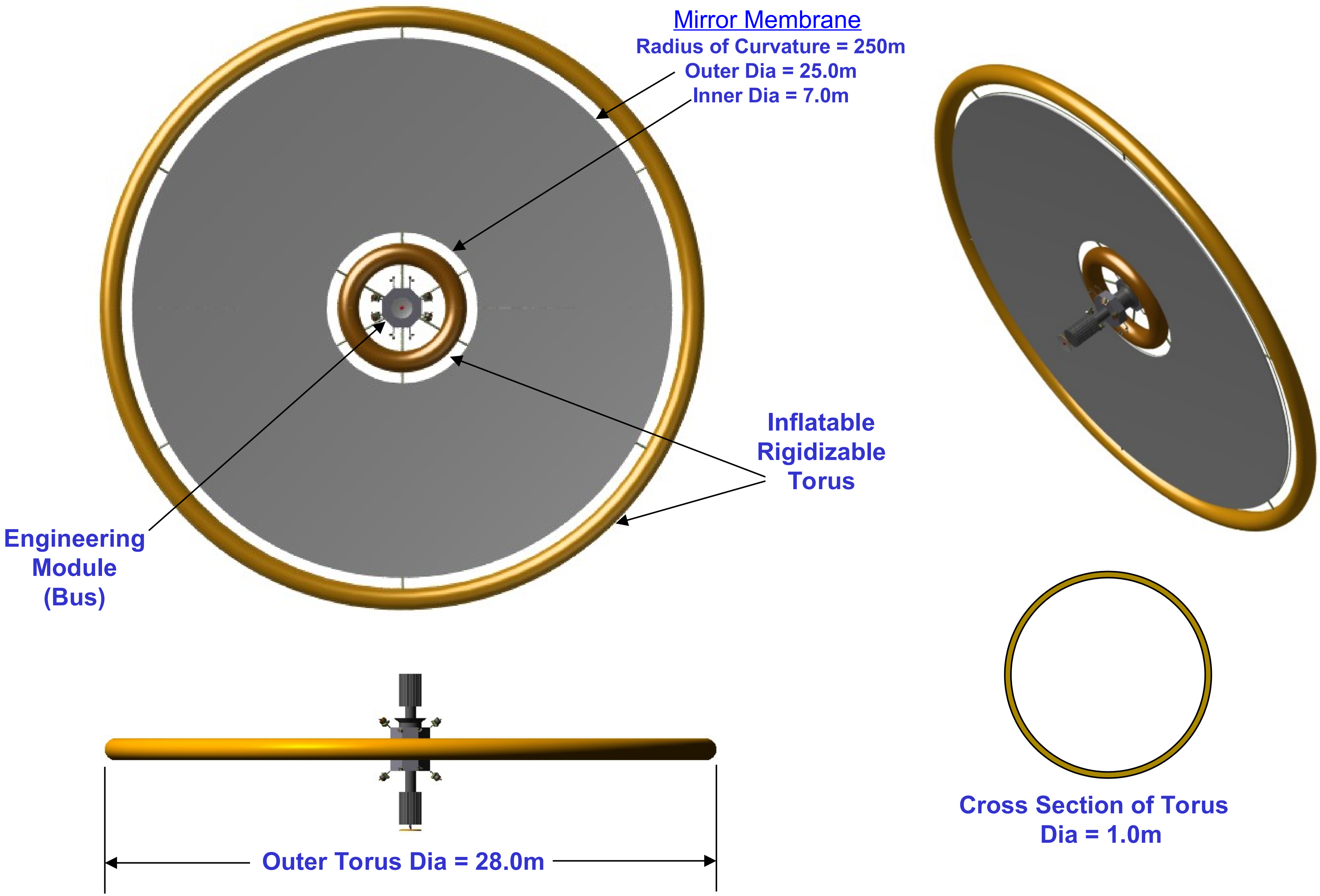


- **25m Aperture primary membrane mirror combined with a secondary Science telescope located 125 m away in formation flying configuration**
- **10 year science operations objective without resupply**
- **24/7 100% duty cycle**

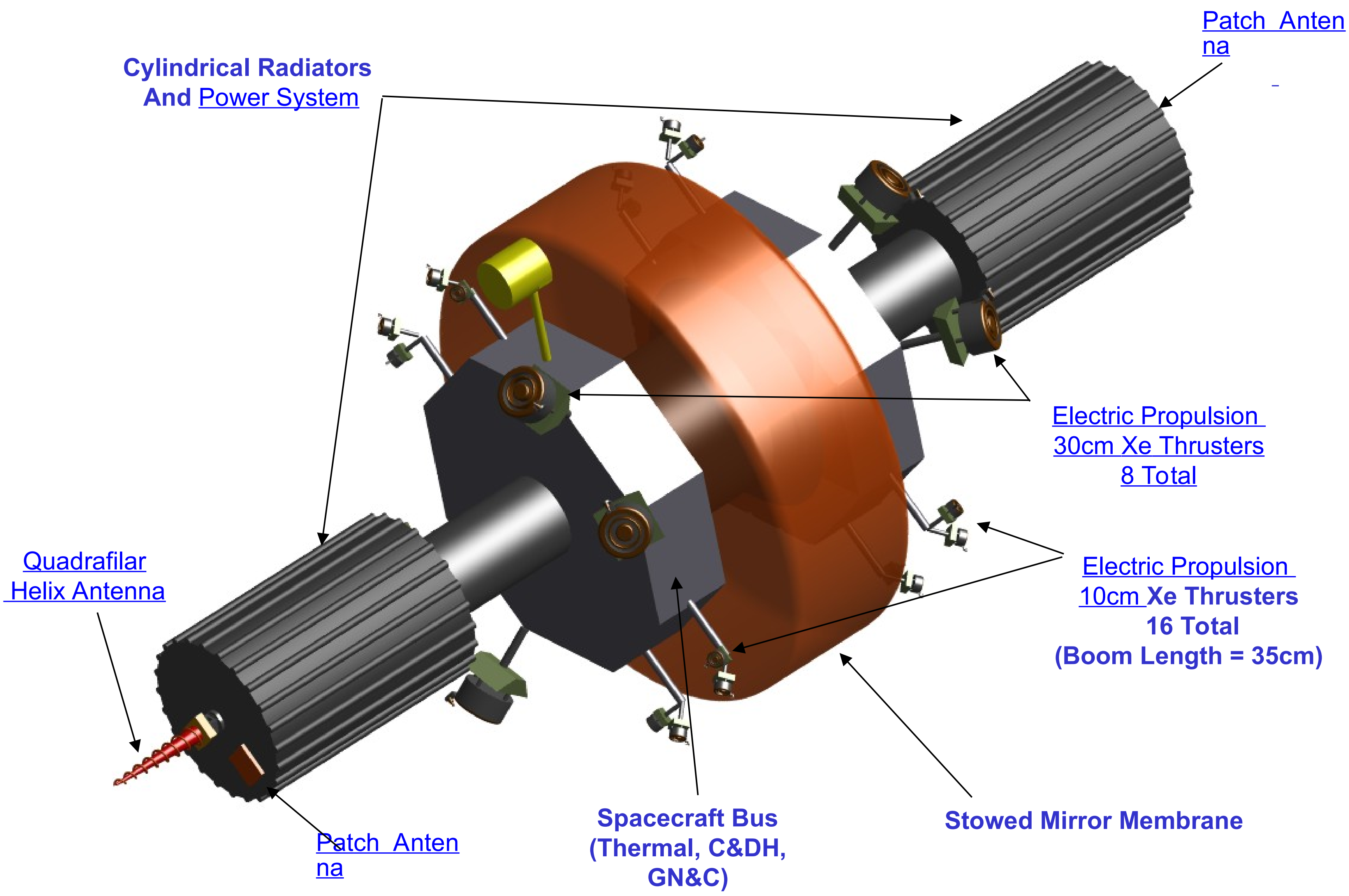
Science Telescope Spacecraft



Aperture Spacecraft - Deployed



Aperture Spacecraft – Pre-Deployment



Delivery to Earth-Sun L2 Mission Trades

-
  - ELV transfer from Earth using a Lunar swingby to a small amplitude libration point orbit about L2, then a low thrust transfer to the mission orbit using spacecraft propulsion systems
- Alternative #1
  - Impulsive Earth escape, then low thrust using a Solar Electric Propulsion (SEP) stage to the L2 point, and final impulsive zero velocity deployment using hybrid Chemical / SEP Carrier Vehicle
- Alternative #2:
  - Launch to LEO, rendezvous/docking with a Nuclear Electric Propulsion (NEP) stage and then low thrust transfer to the L2 point

Baseline Transfer to Earth-Sun L2

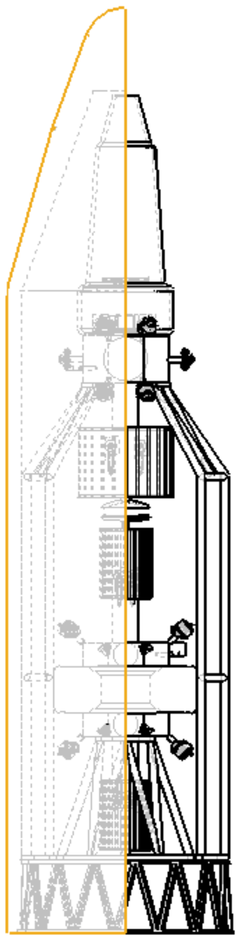
- **The observatory will be deployed in a small amplitude libration point orbit about Earth-Sun L2**

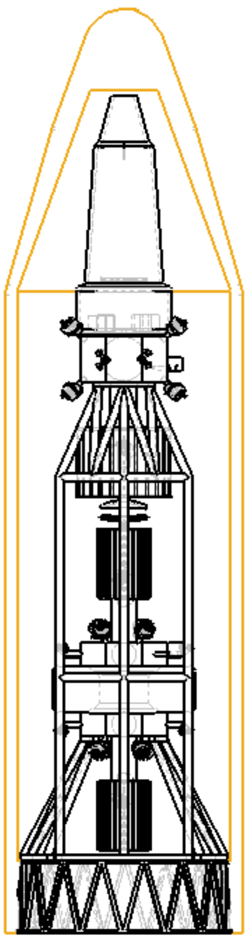
- **Transfer from Earth to the small amplitude libration point orbit would take ~5-6 months (with a Lunar swing-by)**

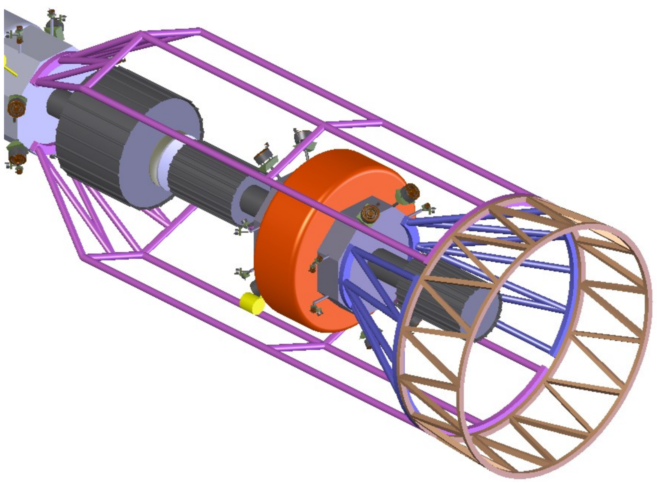
- **The Science and Aperture spacecraft will use their low thrust electric propulsion systems to attain the mission orbit (same system to be used for station-keeping)**

- **Transfer from the small amplitude libration point orbit to the mission orbit will require ~3 additional months and will require a delta V of ~100 m/s**

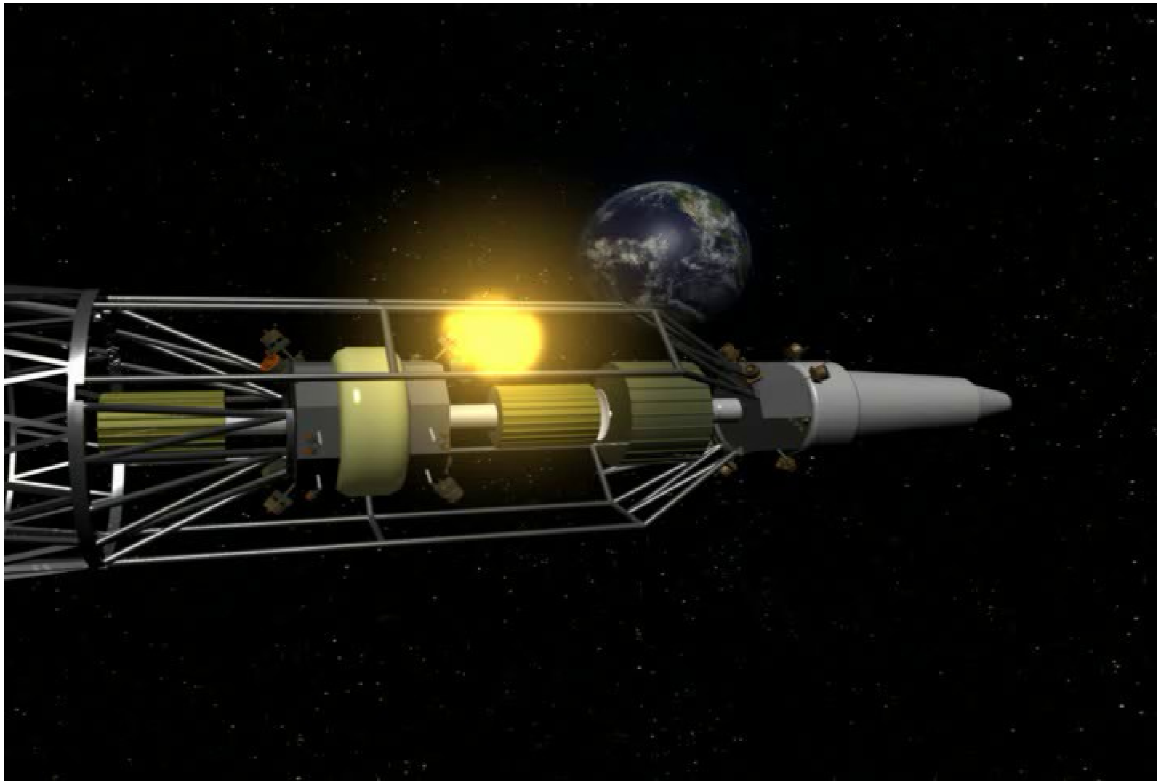
Launch Vehicle Packaging



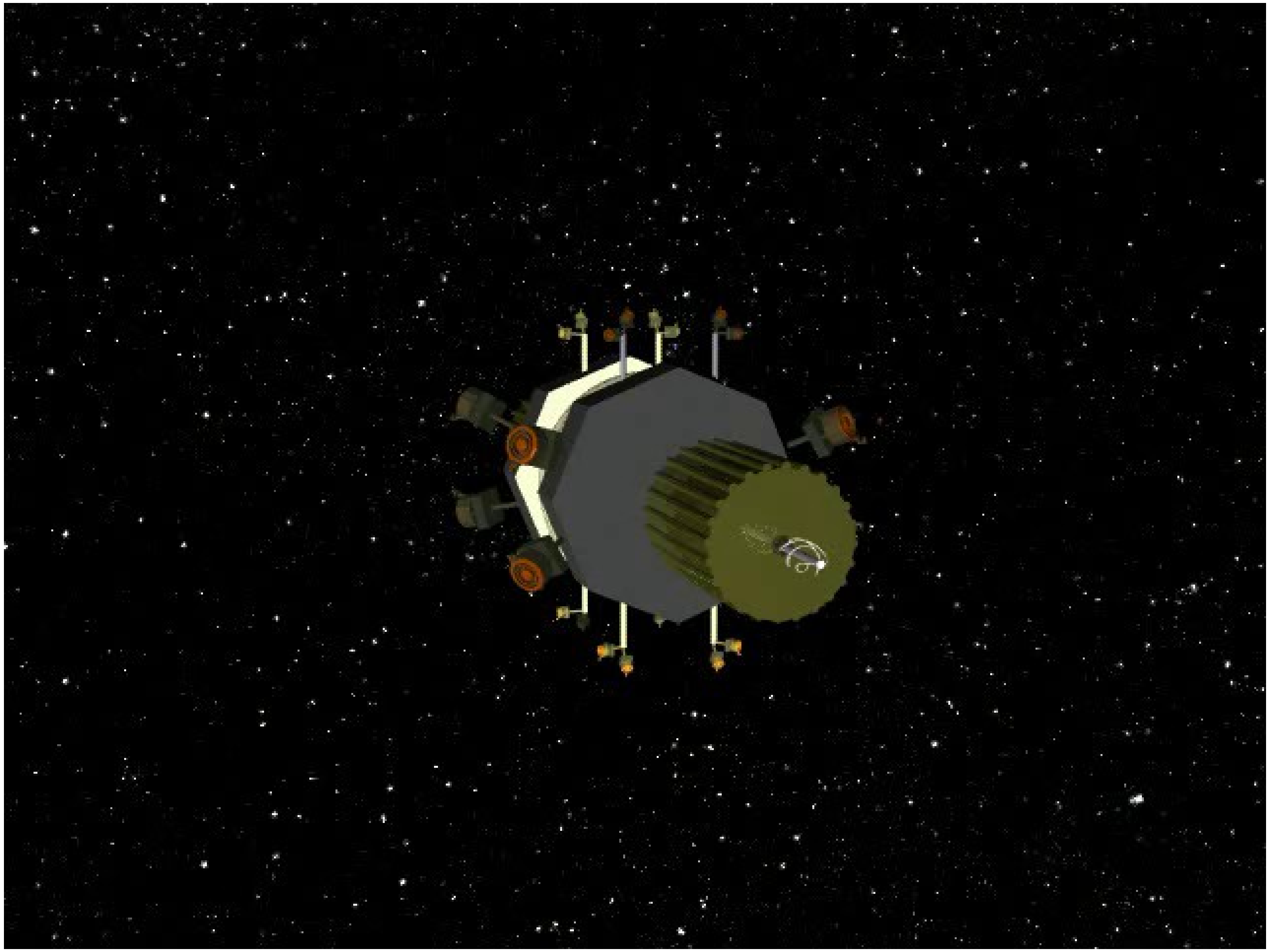




Spacecraft Release from Support Structure



Observatory Deployment



Enabling Technologies

- Miniaturization of Subsystems hardware and science instruments, 3-D electronics, integrated structures/cabling, MEMS sensors and actuators
- Instrument and algorithm technologies
  - Detectors
  - Tomography
- Building of deployable large, low areal density mirrors and their associated structural components for operation at Earth-Sun L2 Environment
- Robust end-to-end modeling of telescope system and validation of system model
- Structures and Control
  - Active Figure Control Concept for Membrane Primary Mirror
  - Lightweight composite structural materials for Telescope and Spacecraft
- Power
  - Advanced Radioactive Isotope Power Sources with high specific power efficiency

Enabling Technologies (cont)

- **GN&C**
  - **Combined High Accuracy Earth-Sun Sensor to maintain Orbit Tracking**
  - **RF and Laser-Optical Metrology Systems for Formation 3-D Knowledge**
  - **Precision Formation Flying and Orbit Navigation Methodologies**

- **Propulsion and Control**
  - **Advanced high specific-impulse linear Xe EP thrusters in large/small sizes**
  - **Sophisticated, higher-order station-keeping controllers that mitigate thruster limitations**

- **Packaging & Deployment**
  - **Packaging for delivery of the primary mirror to Earth-Sun L2, and logistics of its deployment**

Summary

- A concept for an Earth observing capability at the Earth-Sun L2 was developed
  - Study Earth's atmosphere as it occults sunlight
- Powered "orbit" near L2 is needed to maintain observatory position within the annular eclipse
  - Must stay within 200 km of the Sun-Earth line
- 25m Aperture primary membrane mirror combined with a secondary Science telescope located 125 m away in formation flying configuration
  - 10 year science operations objective without resupply
  - 24/7 100% duty cycle
- ELV transfer from Earth using a Lunar swing-by to a small amplitude libration point orbit about L2, then a low thrust transfer to the mission orbit using spacecraft propulsion systems
- Key technologies include lightweight membrane structures

Backup

Study Team

- Edward Mettler – Principal Eng. Invest.
- Ram Manvi – Technical Integration
- Ahmet Acikmese – Controls/Dynamics
- William Breckenridge – System Reqs
- Serge Dubovitsky – Optical Metrology
- Steve Macenka – Optical Design
- Eldred Tubbs – Form. Flying/Metrology

- Joe Zawodny – Science/Instrumentation
- Jeff Antol – Study Integration
- Rosalind Echols – Mission Infrastructure
- John Flick – Technology Assessments
- Shawn Krizan – Configuration/CAD
- Jeff Murch – Graphics/Animations
- Carlos Roithmayer/Linda Kay-Bunnell/ Renji Kumar/Haijun Shen – Orbital Mechanics
- Fred Stillwagen/Bob Stephens – Comm
- Chris Strickland – Structures

- Steve Cooley/Dave Folta/Greg Marr – Orbital Mechanics, Transfer
- Jay Herman – Science
- Jesse Leitner – Distributed Spacecraft
- Quang Nguyen/Ken McCaughey – C&DH
- David Steinfeld – Thermal

- Stan Borowski – GRC Lead
- Bob Cataldo – Power
- Melissa McGuire/Thomas Packard – Launch Vehicle, NEP Transfer
- Tim Sarver-Verhey – Propulsion

Back to Study Team Organization

380nm – 980nm Spectrometer

- **Offner Imaging Spectrometer with 2 focal planes**
- **60µm pixels in a 512 x 512 array using Silicon**
- **Measurements of:**
  - **Ozone**
  - **Aerosols & Clouds**
  - **Tropospheric Water Vapor**
  - **Temperature & Pressure (Oxygen A-Band)**
  - **Altitude Registration using $(O_2)_2$**

Back to Science Objectives

980nm – 2480nm Spectrometer

- **Offner Imaging Spectrometer with 2 focal planes**
- **60μm pixels in a 512 x 512 array using InGaAs**
- **Measurements of:**
  - **Carbon Dioxide**
  - **Water Vapor**
  - **Methane**
  - **Nitrous Oxide**
  - **Ice**

Back to Science Objectives

Mid-IR & GFCR Imager

- **Combination of GFCR and Broadband channels**
- **2.5 to 10.5μm spectral coverage with 20 channels**
- **Measurements of:**
  - **Carbon Dioxide**
  - **Water Vapor**
  - **Methane**
  - **Nitrous Oxide**
  - **Sulfate Mass**
  - **CLO_x, NO_x, and HO_x Members & Sources**
  - **Temperature & Pressure**

Back to Science Objectives

Science Comparison

Item	LEO*	GSFC-L2	RASC-L2
Science Objectives	Very Broad Range	Age of Air Low Res Dynamics	Climate Forcing Climate Response Forecast Model Input Lowest Strat Dynamics Upper Trop Composition Age of Air Strat-Trop Exchange
Vertical Resolution	0.5 to 2.0 km	2 to 4 km	1 km
Vertical Range	2 to 100 km	8 to 30 km	8 to 100 km
Altitude Knowledge	50 to 200 m	1000 m	100 m
Latitude Sampling	1 to 5 deg	> 0.5 deg	0.25 to 1 deg
Longitude Sampling	1 to 24 deg	< 15 deg (sparse)	0.25 to 1 deg
Global Maps	0 to 2 per Day	0 to 2 per Day	2 per Day
Continuous Global Mapping	No	No	Yes
Profiles per Day	from 30 to 200,000	est < 15,000	160,000 to 2,000,000
Duty Cycle (monthly Avg)	6 to 100%	est ~20% ??	100%

* LEO instruments include HiRDLS, HALOE, MLS, SAGE, ACE-FTS
um indicates micrometers

Back to Science Objectives

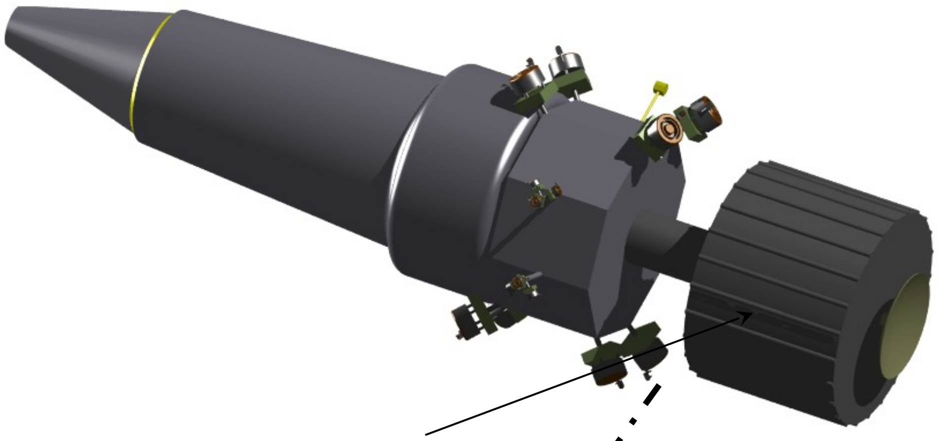
Science Comparison (cont)

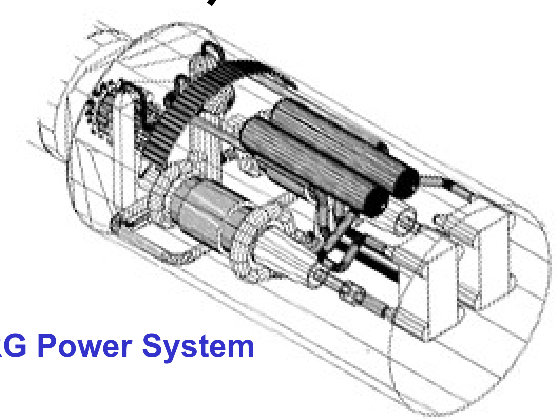
Item	LEO*	GSFC-L2	RASC-L2
Spectral Range	0.2 to 500 um	1 to 4 um	0.3 to 10 um
Measurement SNR	500 - 2000	500	2000
O_3, H_2O, CO_2, CH_4, N_2O, O_2	Yes	Yes	Yes
NO_x, ClO_x, HO_x	Yes	No	Yes
NO_x, ClO_x, HO_x Sources / Reservoirs	Yes	No	Yes
Temperature & Pressure	Yes	Yes	Yes
Aerosols	Yes	No	Yes
Sulfate/Water/Ice/NAT/…	Yes	No	Yes
Needs	Multiple Platforms, Instruments, & Techniques	Increased Sampling Larger Aperture	Technology Advance

* LEO instruments include HiRDLS, HALOE, MLS, SAGE, ACE-FTS
um indicates micrometers

Back to Science Objectives

Science Spacecraft Power System

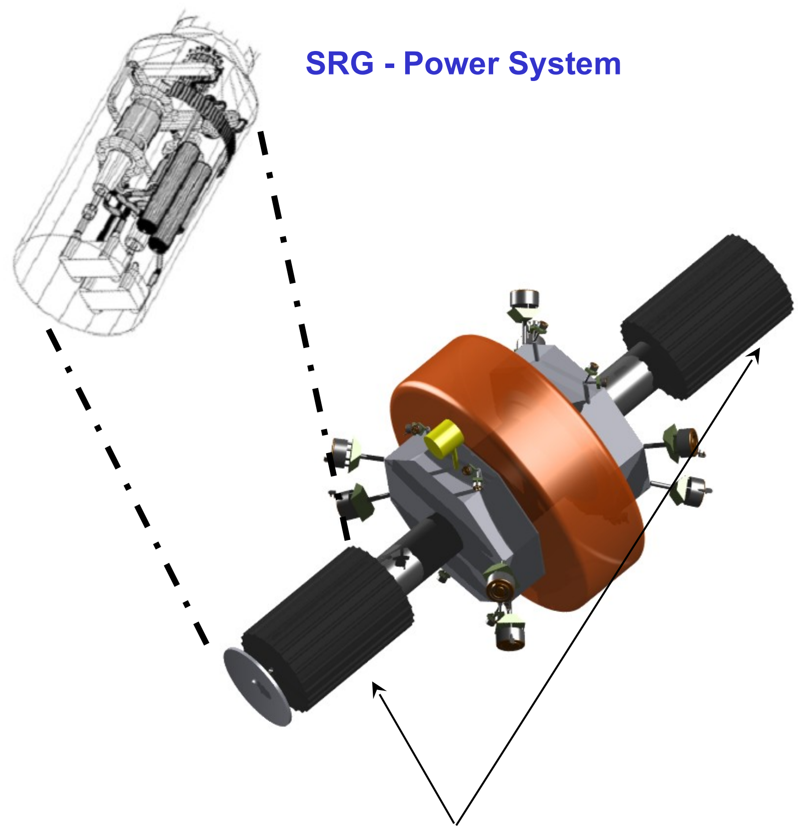




SRG Power System

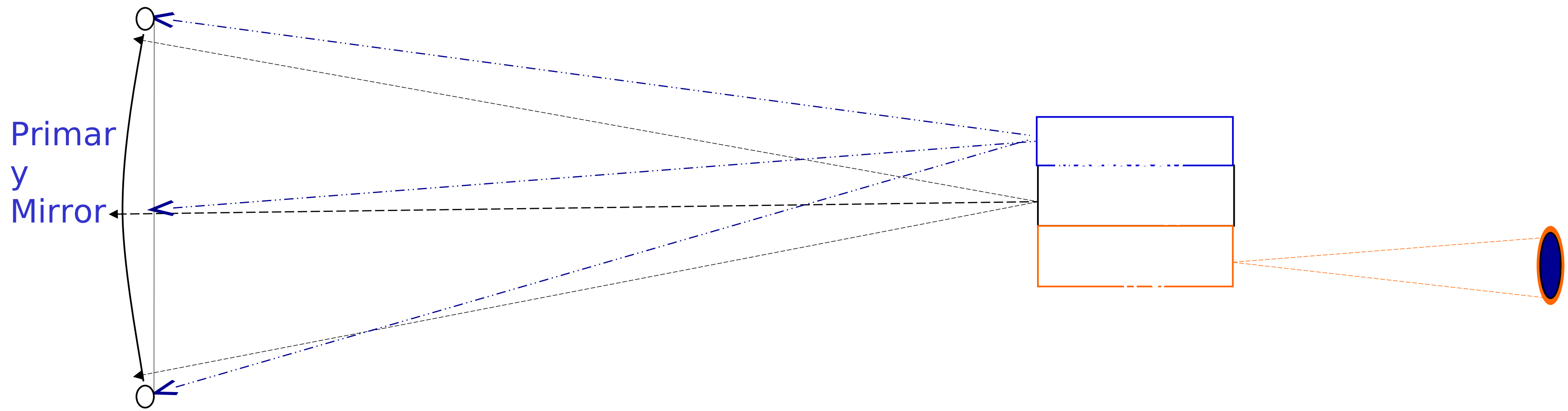
Back to Science Spacecraft

Aperture Spacecraft Power System



Back to Aperture Spacecraft

Metrology Platform on Science S/C



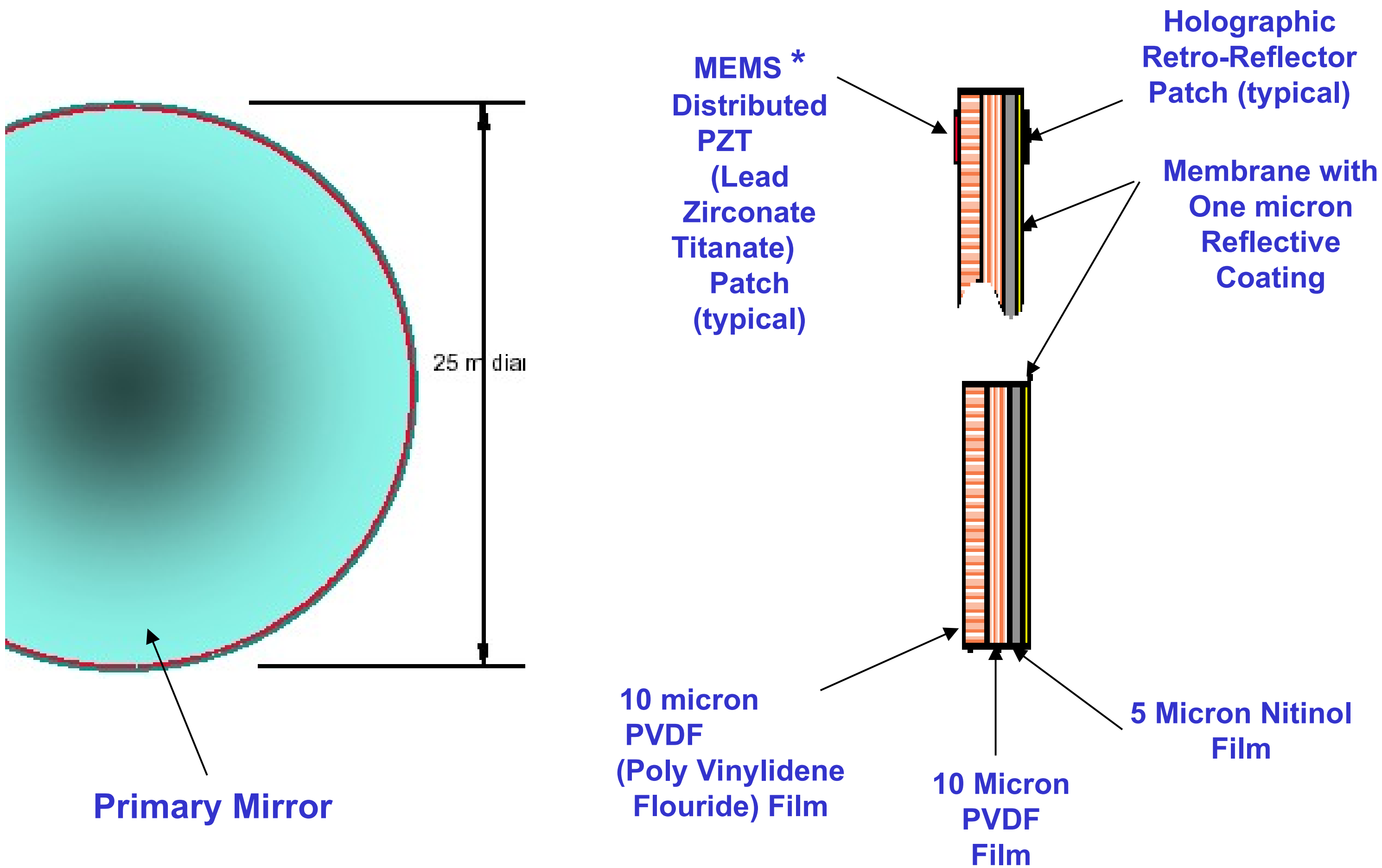
GPS-like range and phase measurement between transmitter and receiver, triangulated to get relative position and attitude of the Aperture S/C for acquisition and coarse formation control.

Laser range & bearing to retro-reflectors on the mirror to get precision relative location and attitude and mirror shape for fine formation control and Earth image location prediction.

Image Earth & Sun to find points on the limbs and determine relative Earth direction, position offset from the Earth-Sun line and coarse Earth range.

Back to Science Spacecraft

Membrane Primary Mirror



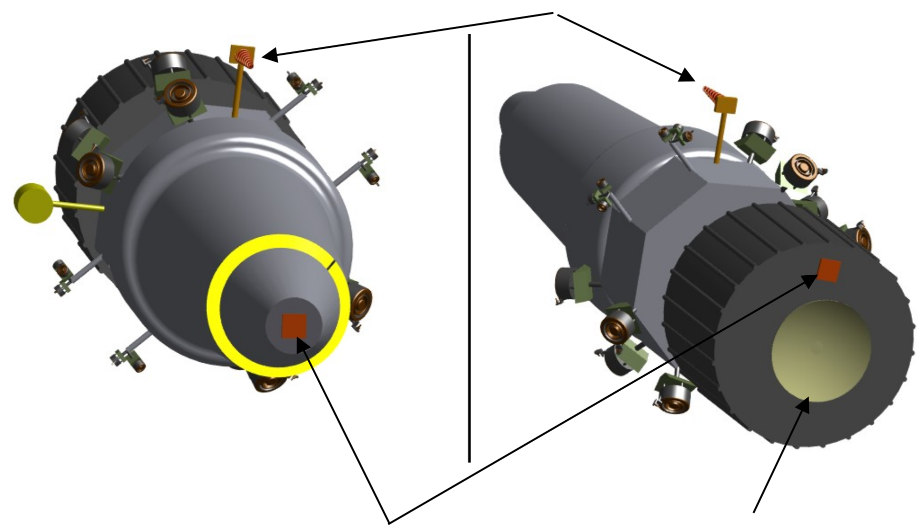
* E-H Yang and S-S Lih, JPL , 2003 IEEE, 0-7803-7651-X/03

Back to Aperture Spacecraft

Science Spacecraft Comm System

Earth

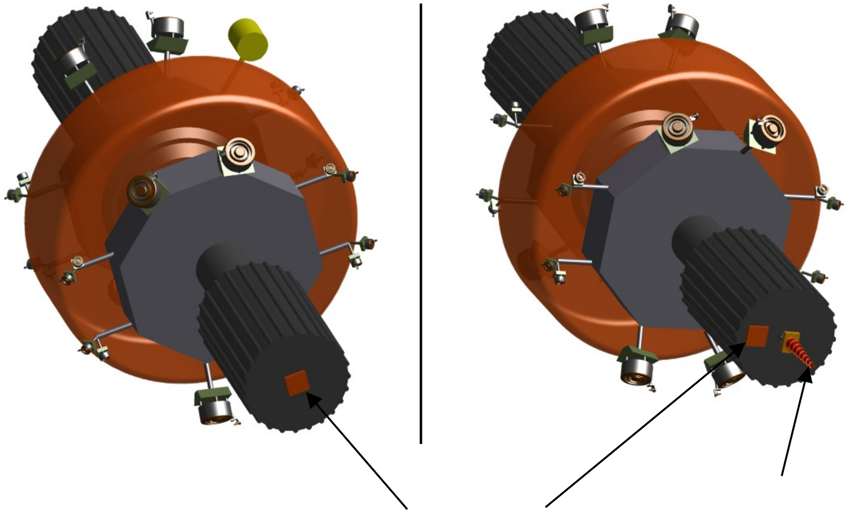
L4/L5 relay(s)



Back to Science Spacecraft

Aperture Spacecraft Comm System

via Earth L4/L5 relay during operations (if necessary)



Back to Aperture Spacecraft

Propulsion System

Back to Science S/C Back to Aperture S/C

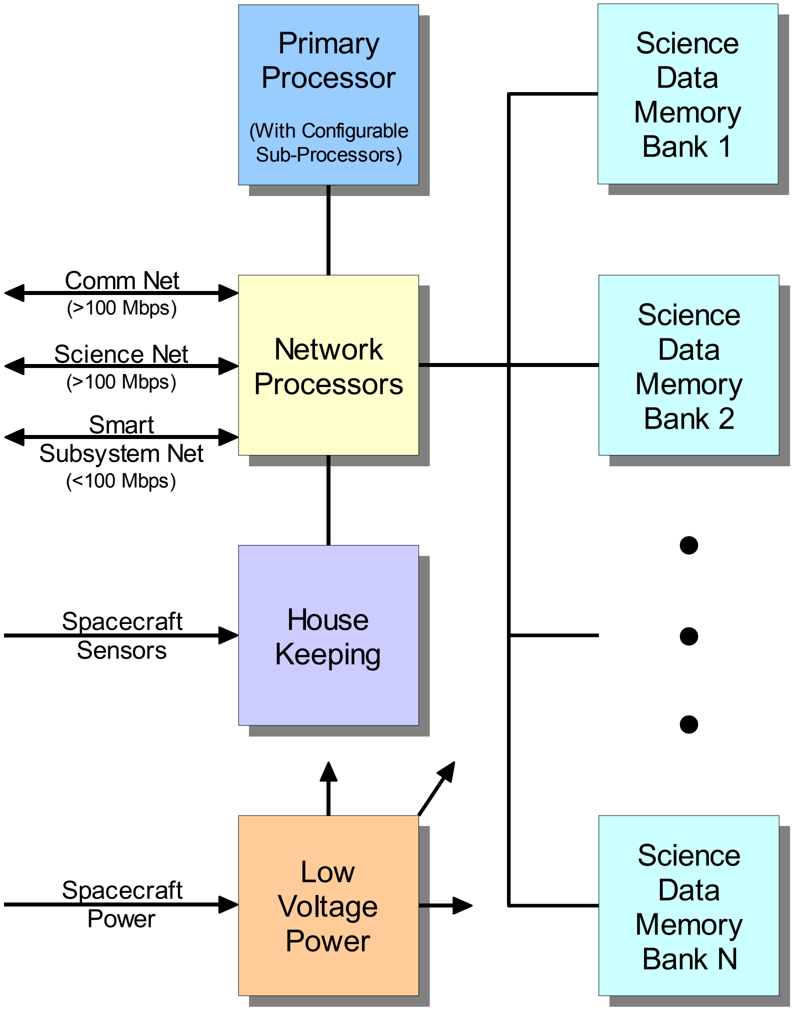
Thermal System

- **Aperture Spacecraft**
  - 7 meter hole in aperture prevents thermal gradients in mirror surface
  - Heat from SRG's can warm engineering module by loop heat pipes. Engineering section needs 140 watts of heat.
  - SRG radiators can dissipate 5000 watts (total) at 60ºC.
- **Science Spacecraft**
  - 1" thick Shuttle Tiles insulate aperture disk from intense heat from mirror. Tile surface = 845ºC. 44ºC substructure temperature.
  - Aperture slit ($10cm^2$) allows 280 watts of heat to enter.
  - Mirror #1 needs to be conductively cooled by heat pipe or heat strap.
  - Science instruments need 185 watts of heat for 20ºC.
  - Bus needs 150 watts of heat. Supplied from loop heat pipe network from SRG radiator.
  - SRG radiator can dissipate 5700 watts at 60ºC.

Back to Science S/C   Back to Aperture S/C

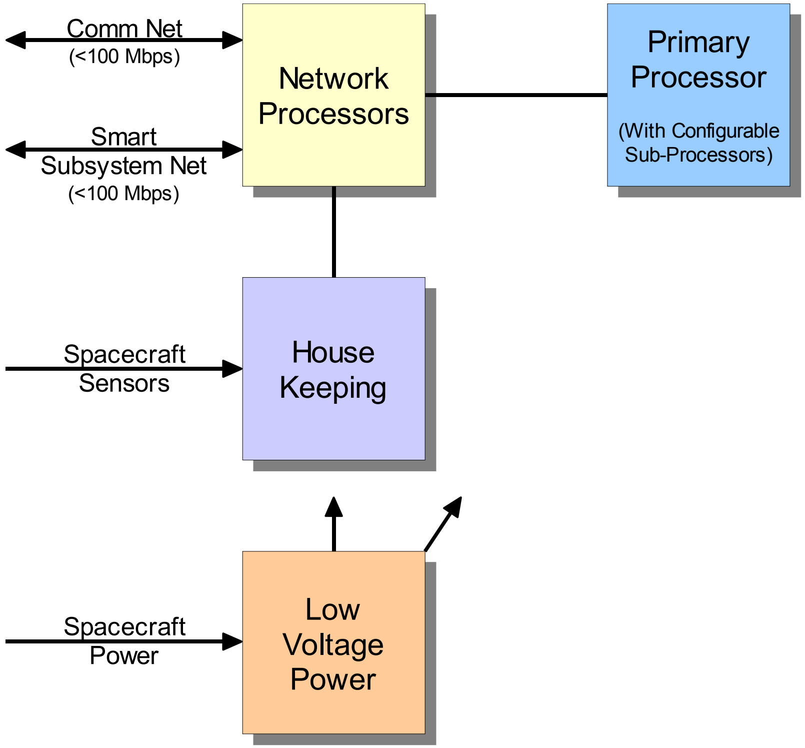
Science Spacecraft C&DH

- Fully redundant (one string shown)
- Uses system-on-chip technology
- Memory banks can be powered down when not needed
- Separate dedicated networks for different functions
- Smart subsystems will reduce C&DH mass & power
- Configurable sub-processor provides for adaptability
- Dedicated local networks to save power
- Scalable design
- Science data rate (2.2Tbit/day)
  - C&DH data storage baseline ~2.2Tbit

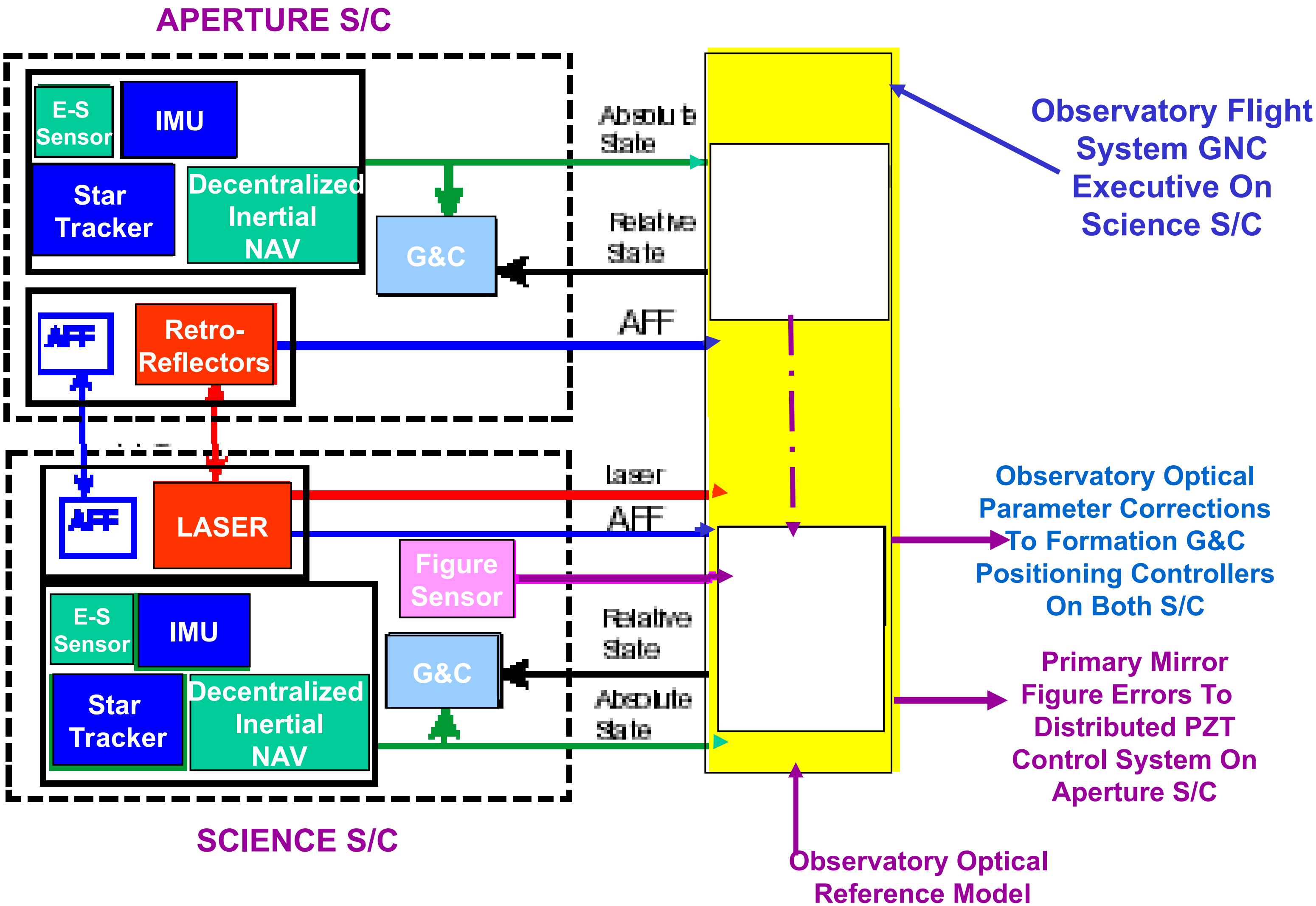


Aperture Spacecraft C&DH

- Scaled down from science spacecraft reusing major components
- Fully redundant (one string shown)
- Uses system-on-chip technology
- Separate dedicated networks for different functions
- Smart subsystems will reduce C&DH mass & power
- Configurable sub-processor provides for adaptability



Formation GNC Concept



Optics Design Drivers

- **Primary Aperture is 25 m diameter to satisfy science 1 km resolution at Earth over broadband spectrum, i.e., Diffraction limit of 67 micro-radian at 10.5 microns. Theoretical size is 19 m with added margin for membrane boundary conditions.**

- **Earth-Sun are extended objects viewed from L2 and require a Spherical Aperture system or *Schmidt Telescope* concept to handle wide angle and high resolution**

- **Separated S/C optics are required by the desired Primary f/10 focal ratio (to minimize aberrations) with 250 m focal length and 500 m center of curvature (c-c).**

- **The *Schmidt* spherical aberration Corrector Mirror, normally located at the (c-c) in a monolithic system, must be re-imaged to locate inside the secondary (Science) S/C Telescope. This is called a "Reduced Schmidt" design and adds complexity.**

Optics Design Drivers (cont)

- excessively large
- The f/5 mass is < 1/10 th the f/10 Telescope.

Optics Implementation Trades

- extremely large and massive, powered orbit near L2
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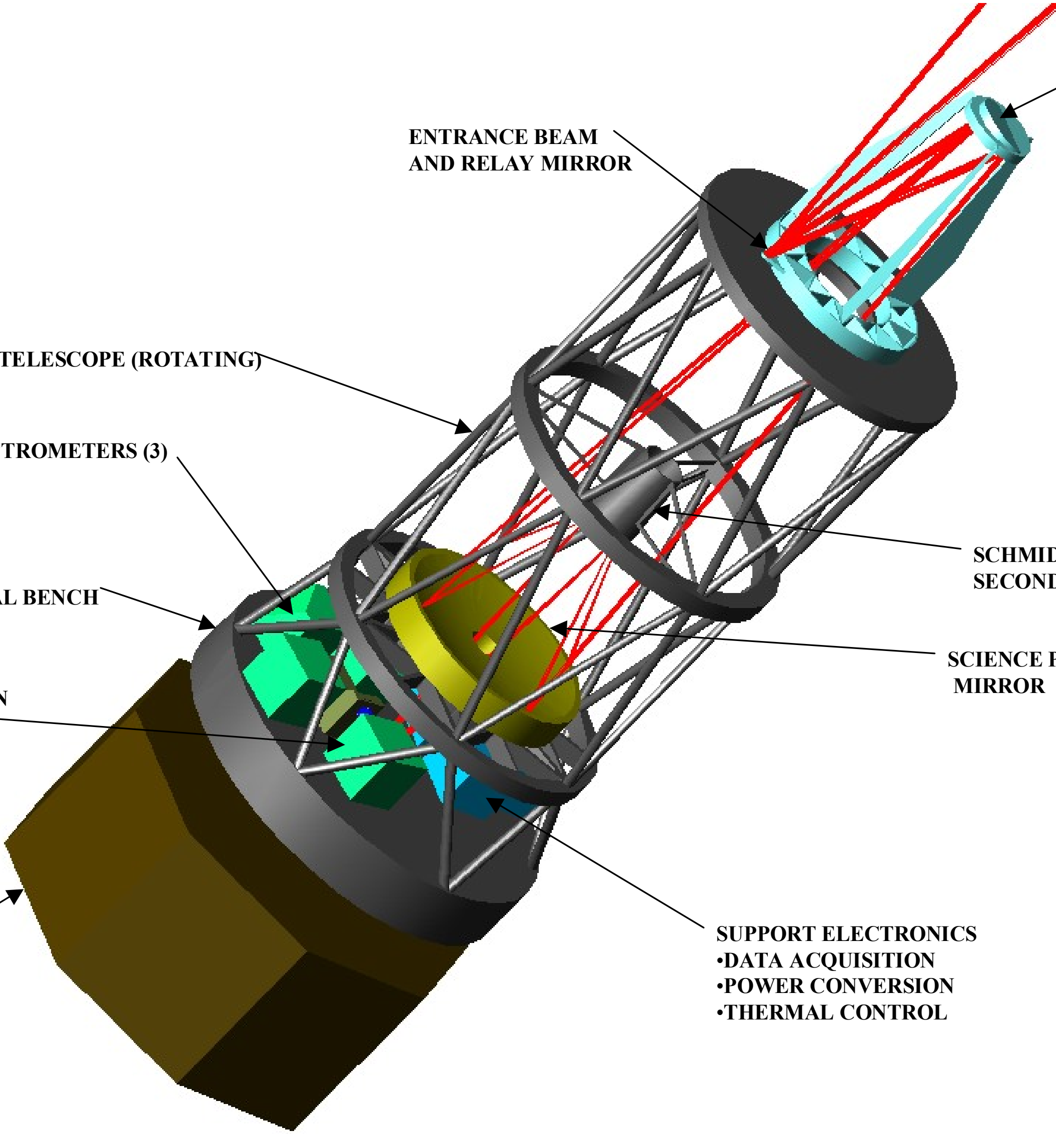
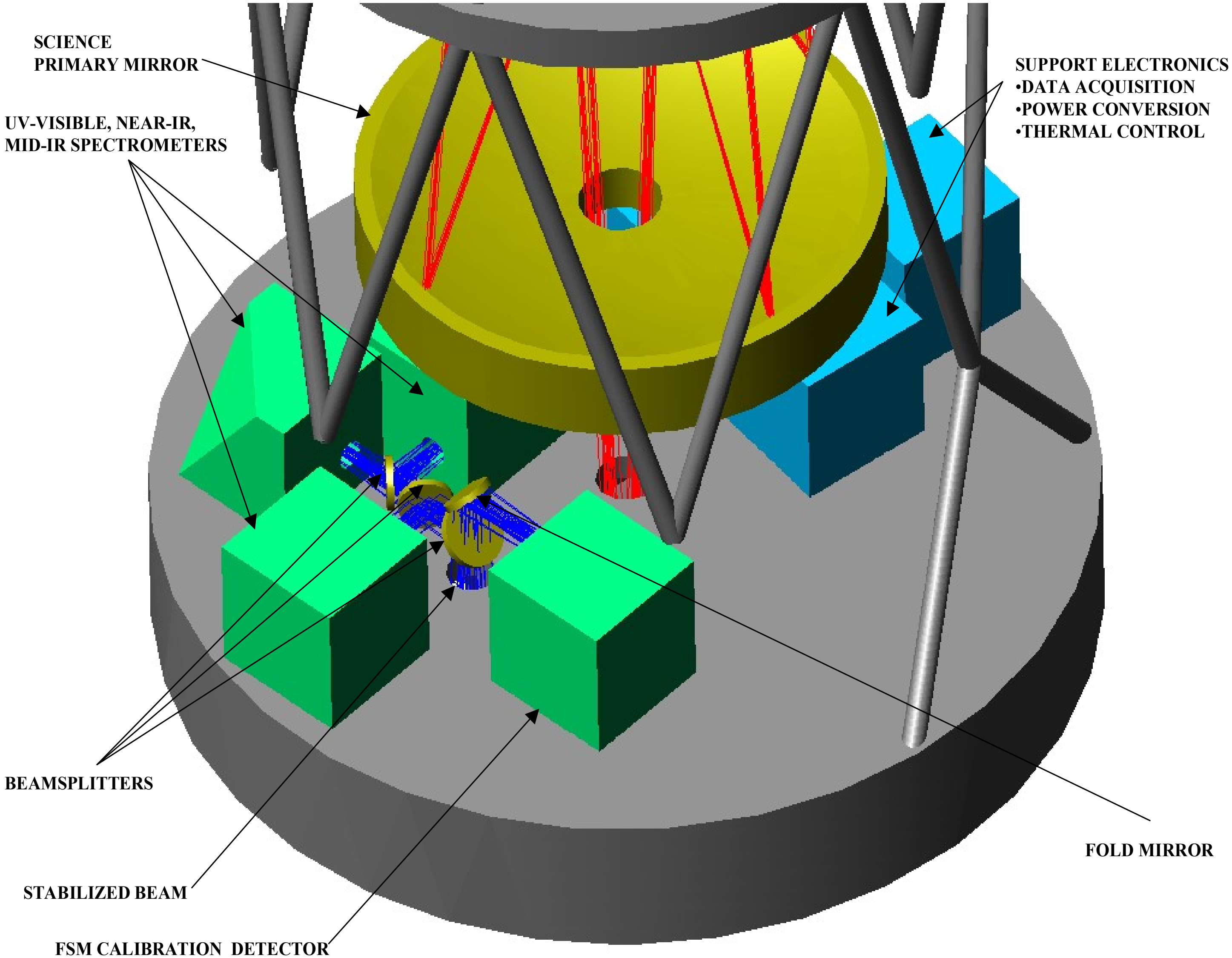
-

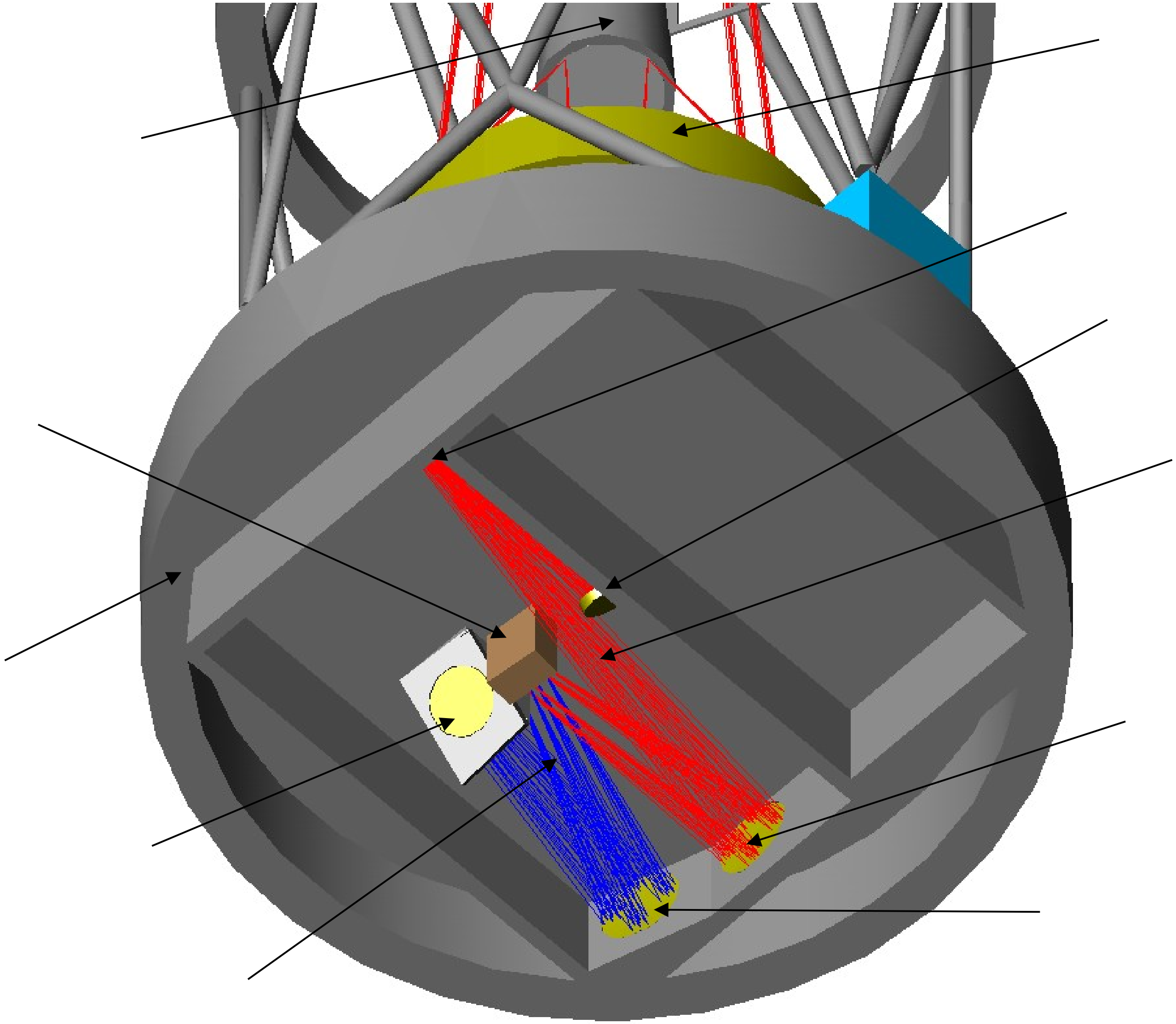
Science Telescope Optics Design



Science Telescope Optics Detail



Science Telescope Optics Detail



SEP Transfer to Earth-Sun L2

- **A direct transfer trajectory using Solar Electric Propulsion (SEP) was briefly analyzed**

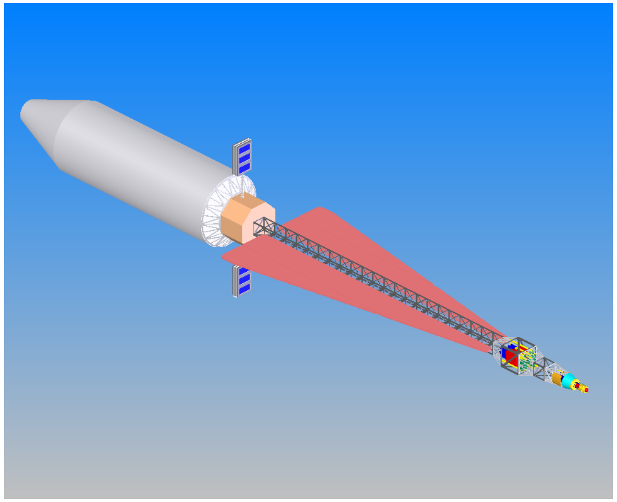
- **Large amplitude L2 libration point orbit would not require a Lunar swingby but would require a launch vehicle C3 of app. –0.6 km^2/s^2 and an increased delta_v for transfer from the large amplitude libration point orbit to the mission orbit**

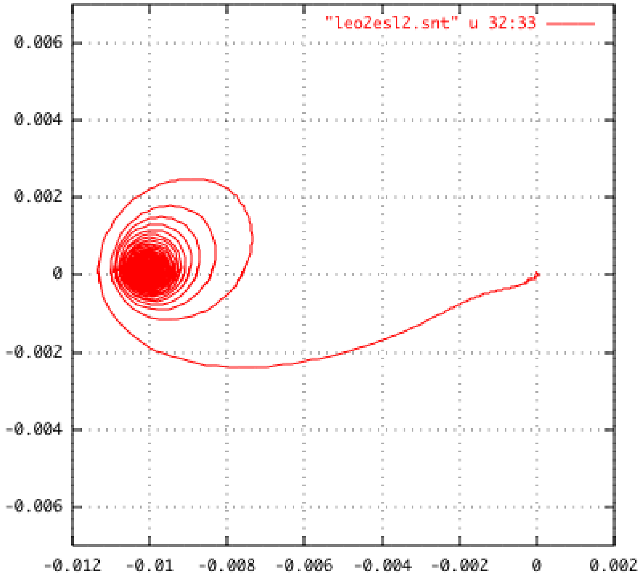
- **However, as the assembly approaches the target orbit it will enter Earth shadow (apparently for some time) and decrease the Solar array power available for the SEP thrust.**
  - **Both spacecraft would need to be deployed prior to Earth shadow entry to complete the final portion of the trajectory using their propulsion systems**

Back to Mission Trades

NEP Transfer to Earth-Sun L2

- **Direct low thrust transfer to Earth/Sun L2 (ESL2)**
- **Use Low thrust (NEP) stage to transfer the Observatory from Earth to the ESL2 point**
  - L2 telescope delivered to LEO of 1000 km by Delta IV H and docked with NEP transfer stage in orbit
  - NEP Transportation Stage assumed to be already on-orbit, previously delivered to Nuclear Safe LEO (1000 km)
- **Time to ESL2 arrival = 494 days**





Back to Mission Trades