A 3D rendering of the OpTIIX telescope assembly mounted on the International Space Station (ISS). The assembly is a complex structure of white and grey components, including a large orange solar panel on the left. A blue circle highlights a specific component, a gold-colored rectangular structure, which is likely the primary mirror or a related optical element. The background is a dark space with stars.

OpTIIX: An ISS-based Testbed Paving the Roadmap toward a Next Generation, Large Aperture UV/Optical Space Telescope

Kenneth G. Carpenter, Shar Etemad, Mike McElwain, Bernard D. Seery, Harley Thronson (NASA-GSFC), Gary M. Burdick, Dan Coulter, Renaud Goullioud, Joseph J. Green, Fengchuan Liu (JPL, CalTech), Kim Ess (JSC), Marc Postman, William Sparks (STScI), and the OpTIIX Team

UV Astronomy: HST and Beyond Conference, June 26, 2012

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OpTIIX: What, Why, and When?



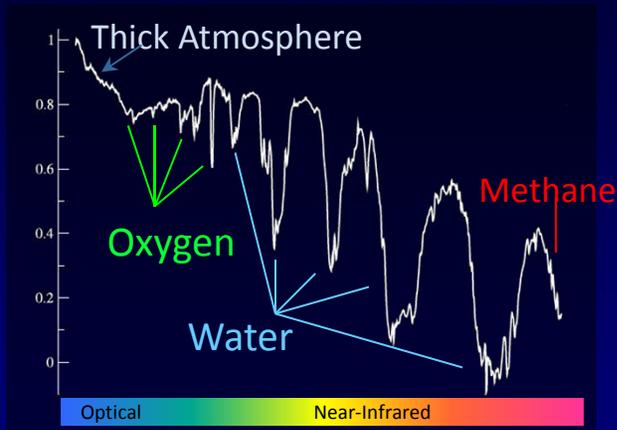
- **What is the Optical Testbed and Integration on ISS eXperiment (OpTIIX)?**
 - An ISS-based testbed to demonstrate that a large optical system can be robotically assembled in space from separate elements launched using existing modest-sized launch vehicles and autonomously phased-up via active optics to produce diffraction-limited images (intrinsically tolerant to ground-based figure errors)
- **Why OpTIIX?**
 - To demonstrate that the mission cost curve and risk can be lowered substantially by use of innovative new technologies, so that future large space telescopes can be enabled ~10 years sooner than otherwise possible. OpTIIX will provide:
 - A powerful ISS asset for testing advanced optical systems. After the initial phase SALMON-type RFPs are possible for further new technology/science investigations
 - An inspiring and broad E/PO opportunity that can engage students/amateur astronomers via a program analogous to Harvard's Micro-Observatory Initiative
 - A potential opportunity to obtain limited but unique science from ISS
- **When OpTIIX?**
 - Currently in Phase B, with launch as soon as March 2015



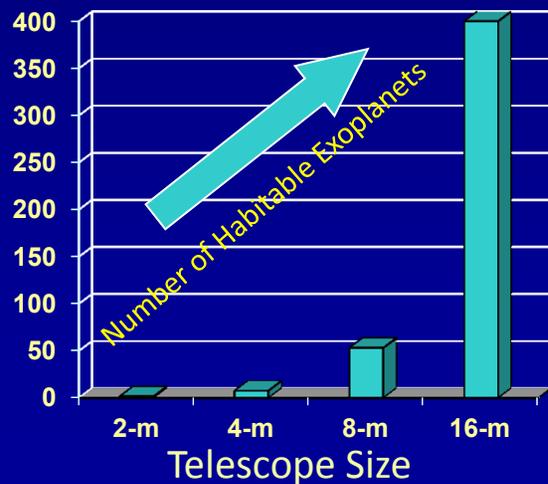
A Large Space Observatory is **Required** to Understand the Earliest Universe and to Detect Life on Exoplanets



Is There Life Elsewhere in the Galaxy?

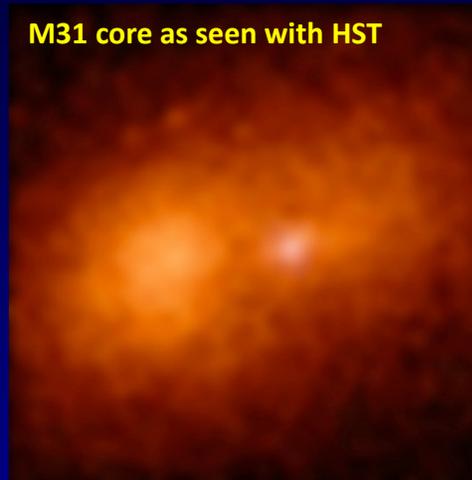


The signature of life is encoded in the spectrum of the Earth

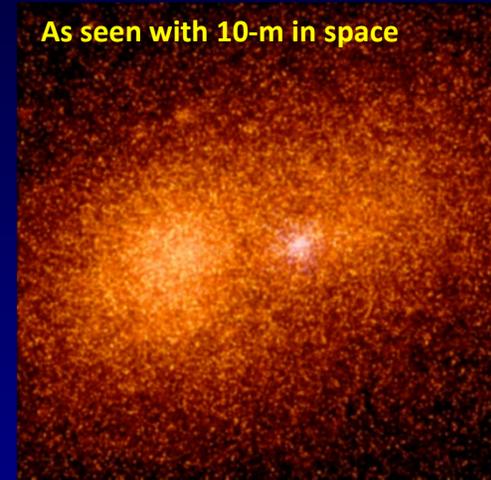


What are the Fundamental Processes that Govern Early Galaxy Formation?

M31 core as seen with HST



As seen with 10-m in space



Distant Galaxy in UDF



Reveal >10x more detail than HST in <5% of the time:
Discover astrophysical knowledge that would otherwise be infeasible from any other facility.

Searching for Earth 2.0

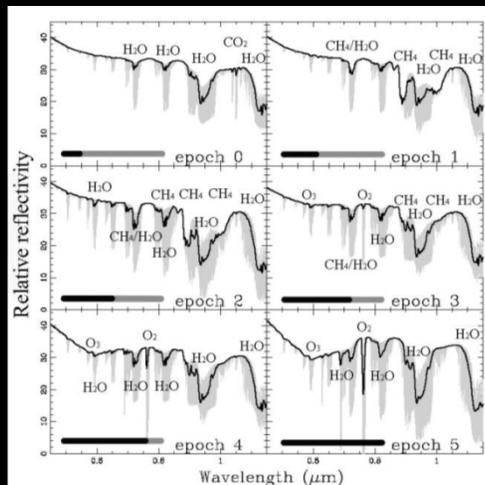


The number of observable candidates $\propto D_{\text{Tel}}^3$

If $\eta_{\text{Earth}} \times \text{prob. life} < 1$

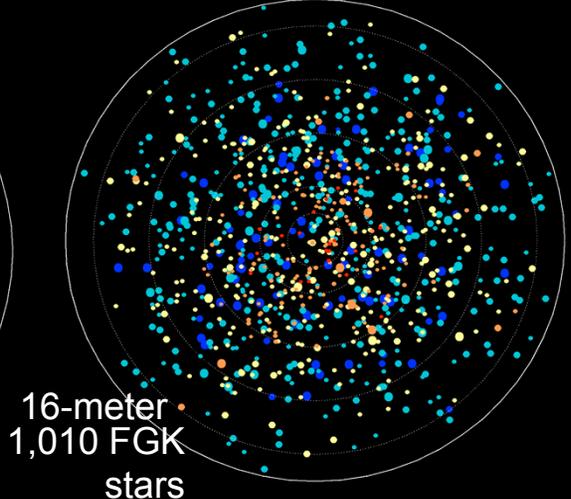
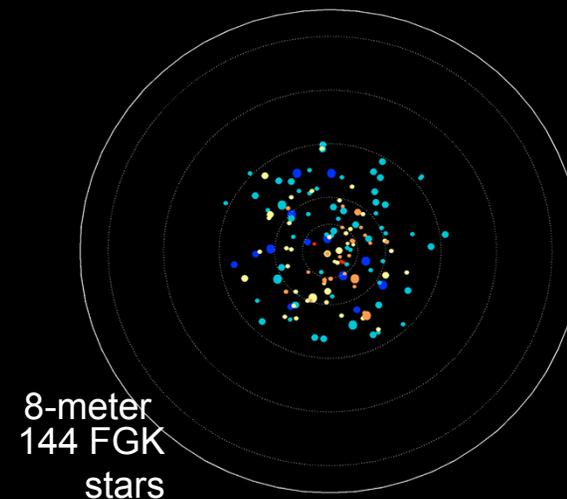
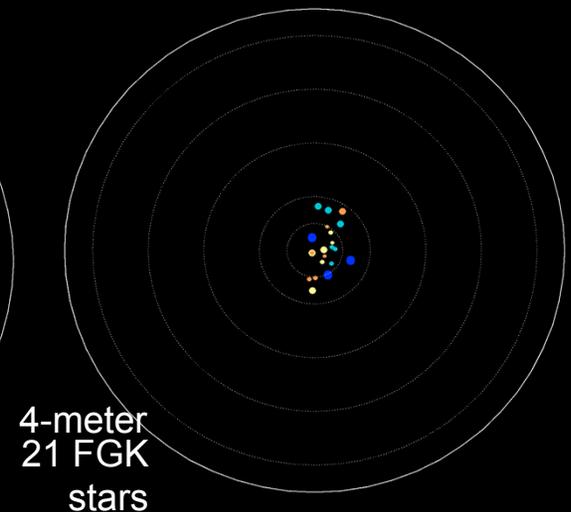
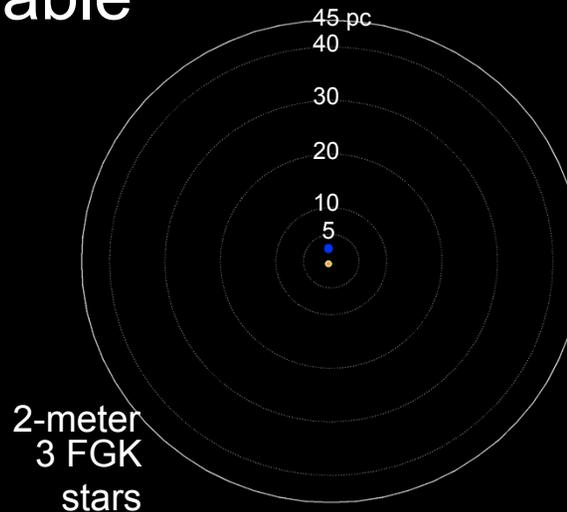
To get spectra

$D_{\text{Tel}} > 4\text{m}$



B-V Color

- < 0.4
- 0.4 - 0.6
- 0.6 - 0.8
- 0.8 - 1.2
- > 1.2





OpTIIX – An Innovative Approach



The space mission cost curve can be redefined

- By leveraging previous technology investments and the ISS infrastructure, we can build a *diffraction-limited* optical 1.5-meter class space telescope for ~\$125M.
- This OPTIIX technology investment would enable NASA to reduce the cost of a 3-meter class space telescope by ~60% , and make a future 8-meter class space telescope an affordable mission for the future.
- OpTIIX lays the technological foundation for bold missions that are affordable in the near-term, not the distant future and retires significant technical risk in advance of the 2020 NRC Decadal Survey.
- An investment in OpTIIX will enable NASA to maintain its global leadership in space science by continuing to do inspirational and revolutionary science .

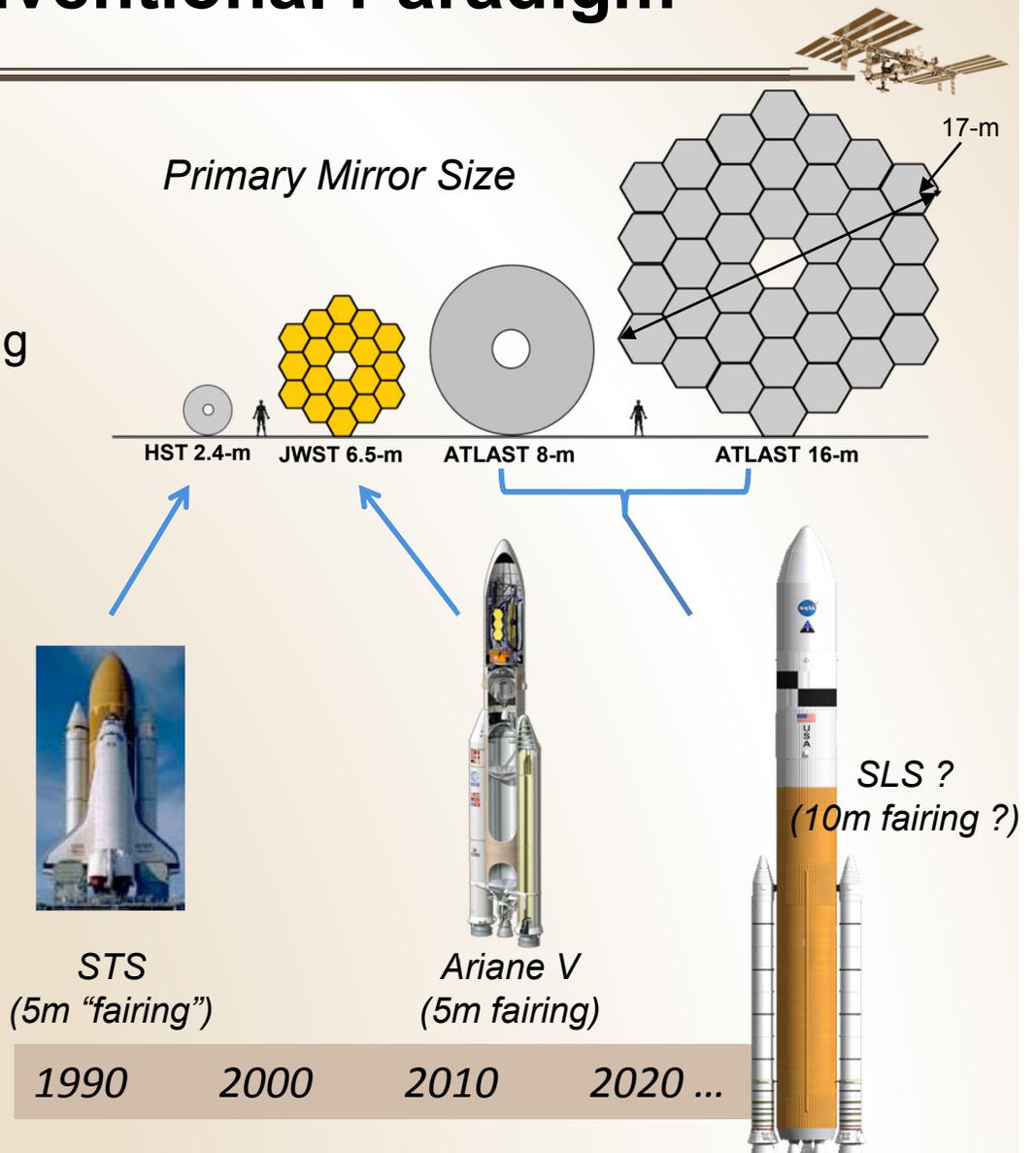
The Conventional Paradigm

Future large space telescopes with conventional monolithic or pre-assembled segmented mirrors face substantial scaling challenges including

- Testing in 1 g
- L/V throw weight & fairing size
- Complex, precision deployments on-orbit
- Long-term performance
- High cost

The conventional paradigm relies on future heavy L/V, large fairings and complex geometry

We believe there is a better way!



Increasing aperture drives cost and complexity geometrically



The New Paradigm to be Demonstrated by OpTIIX



- Build a modularized, actively controlled, segmented *scaleable* telescope by robotically assembling components in space and autonomously phasing it up to diffraction-limited performance
 - Modules launched separately to ISS and robotically assembled
 - Uses lightweight, low-cost, deformable mirror segments
 - Uses active wavefront sensing and control and laser metrology
 - Assembled to mechanical tolerances (~sub-mm precision) and aligned, figured and controlled to optical tolerances (~nm level)
 - Will be an on-orbit testbed for future NASA telescope and science instrument development and a centerpiece for STEM outreach.

These 3 capabilities are already developed & demonstrated to TRL 4-6 through ongoing non-NASA funded technology development at JPL

- Aperture size is no longer limited by manufacturing, ground testing, launch and deployment constraints
- Intrinsically tolerant to imperfections anywhere in the optical chain arising during manufacturing, launch, assembly or operation
- Eliminates need for large system level ground I&T facilities

Partners: GSFC, JPL/CIT, JSC, STScI

Sponsors: ISS Program, OCT, and SMD

Enables new possibilities for affordable space telescopes

OpTIIX Modules

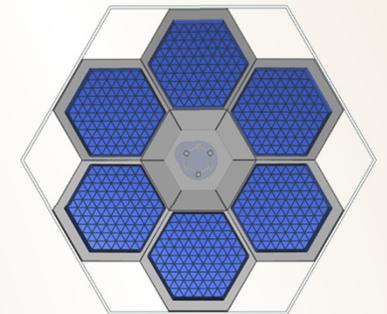
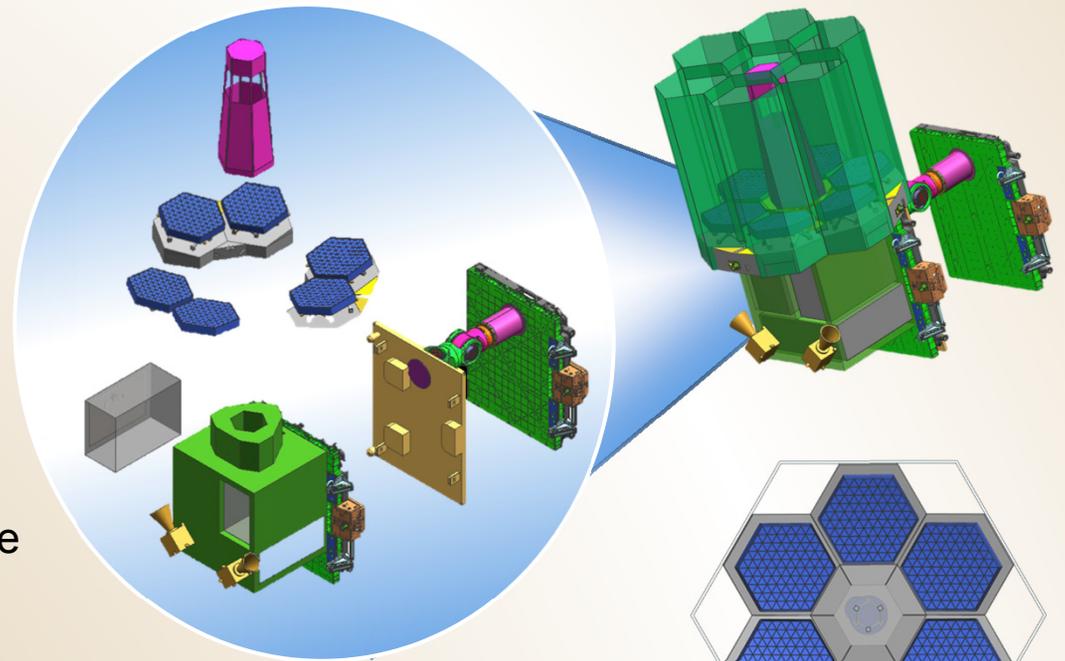


- **Modularized for ISS Integration**

- Standard Robotic and ISS FRAM interfaces
- No EVAs baselined
- Flexible launch options (HTV/Dragon)

- **Telescope**

- 1.45-m, 6-segment telescope
- Diffraction-limited performance in the visible
- On-demand figure and alignment control for performance maintenance



1.45 m aperture
50 cm diameter segments

- **Pointing Control**

- Reusable 3-axis gimbal to enable ISS based observations
- Internal fast-steering mirror to stabilize imaging

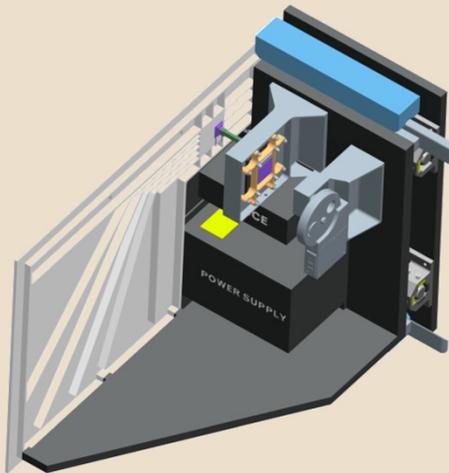
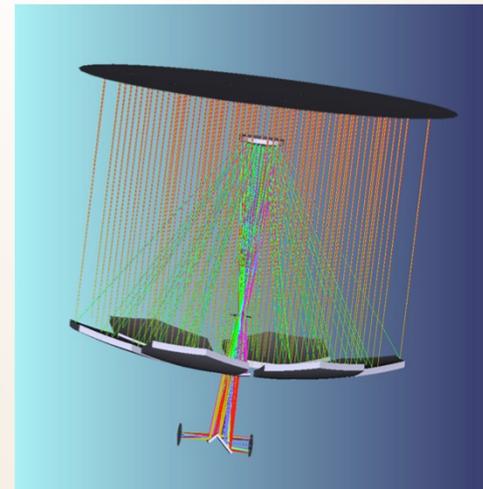
- **Instruments**

- Wavefront Sensing Instrument for characterization and maintenance
- Camera for demonstration imaging
- Capability to replace science instruments

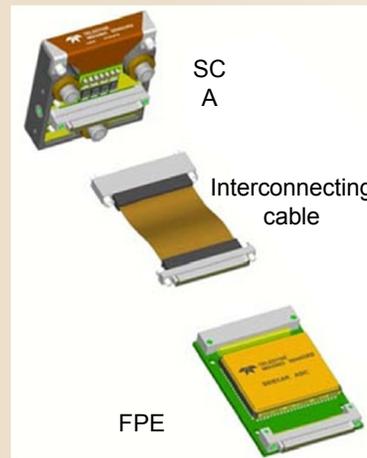
OpTIIX Telescope & Camera Design



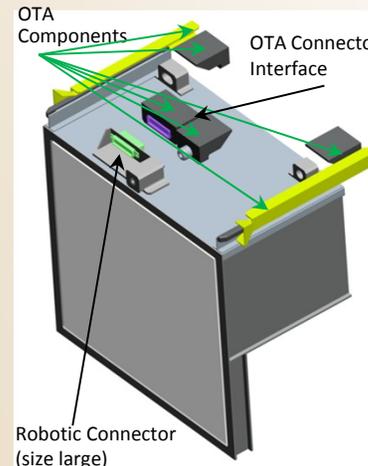
- Three-mirror anastigmat telescope.
 - 1.45-m aperture with 60% fill factor
 - 6 actuated primary mirror (50-cm) segments.
 - Warm telescope (~20 C).
- Simple Imaging Camera built from COTS parts:
 - NRL/JMAPS Program to provide 4k x 4k CMOS FPA, in exchange for OpTIIX bringing it from TRL-6 to TRL-9
 - 3 x 3 arcmin field of view
 - 80% telescope throughput from 450-850nm
 - 40 nm rms wavefront error (80% Strehl ratio)
- Robotic replacement of camera enabled by handling fixtures and precision latches derived from WFC3.



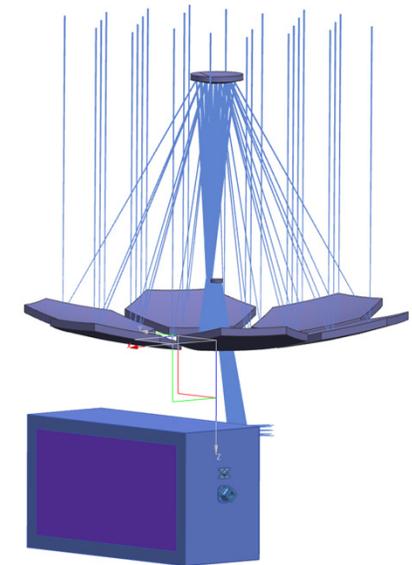
Cutaway view of the imaging camera shown inside GSFC enclosure



Teledyne Detector & Focal Plane Electronics



Robotic Connector and Precision Guide Rails



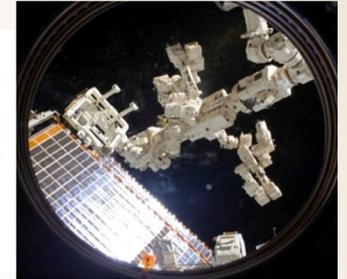
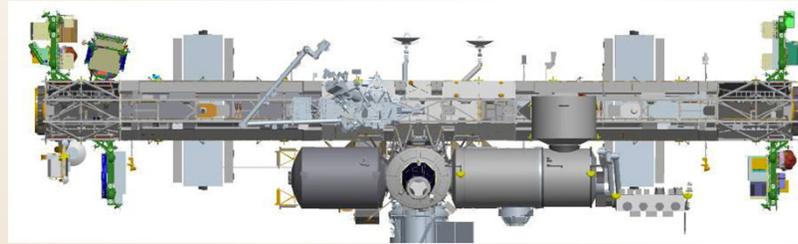


What Enables This Concept?

Well Established ISS Interfaces and Robotics



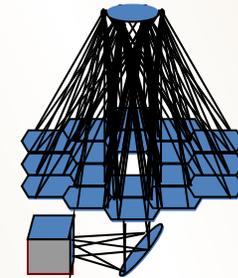
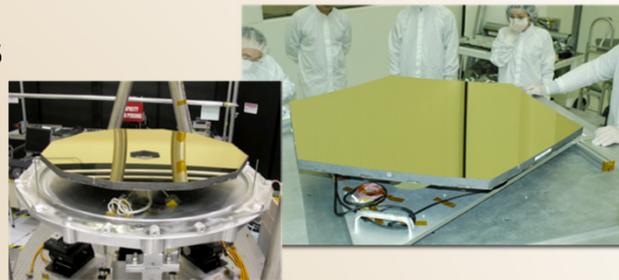
- A completed International Space Station and its supporting infrastructure – **(NASA and International investment)**



Actuated Hybrid Mirror Technology

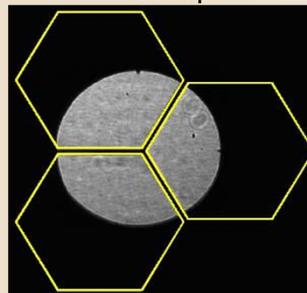
Compact Laser Metrology

- Nanolaminate Active Mirrors and Laser Metrology – **(DOD investment)**

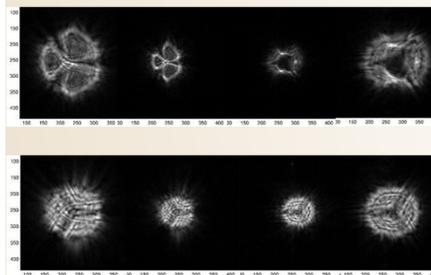


- Multi-segment telescope wavefront detection and correction capability – **(NASA and DOD investment)**

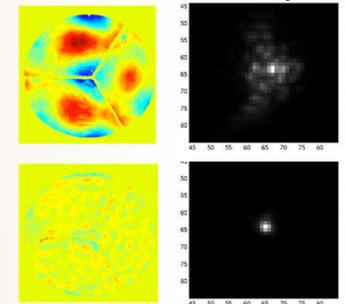
JWST Wavefront Control Testbed with Segmented Telescope



Science Camera Measurements



Wavefront Image of Laboratory Star



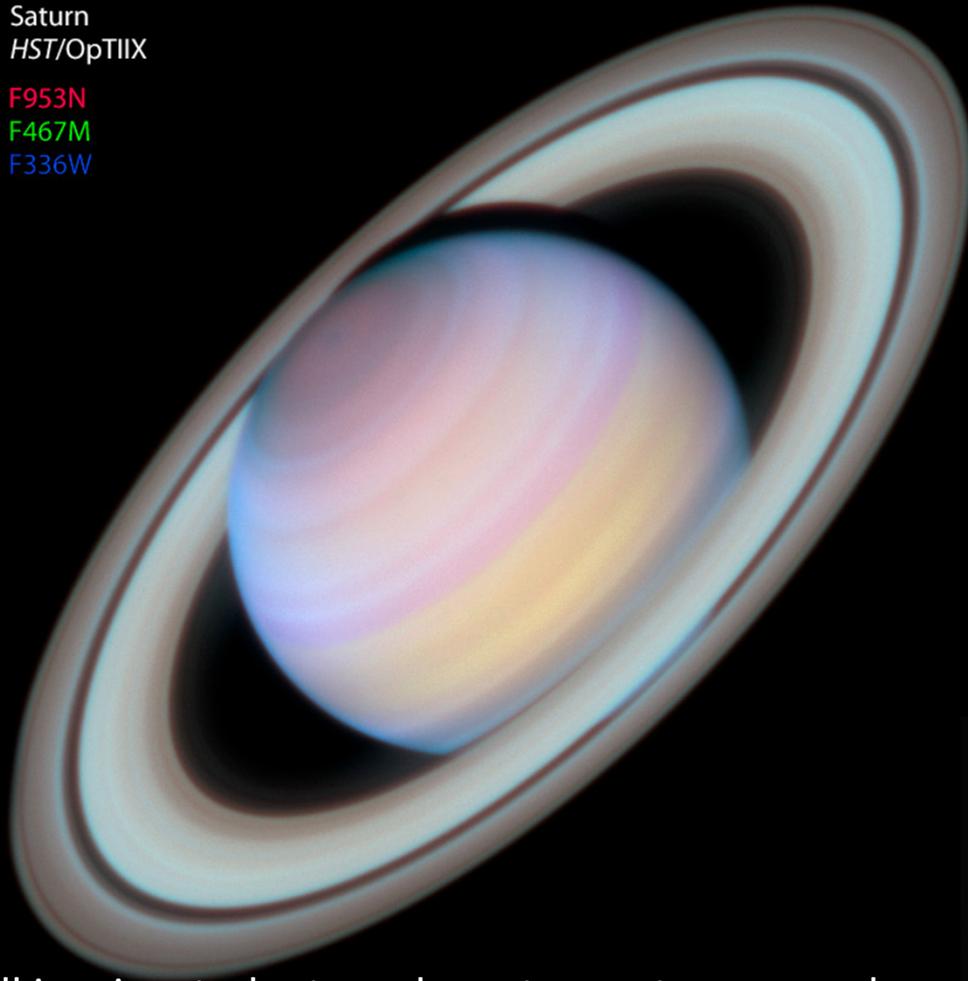
OpTIIX Imaging Performance



Simulated OpTIIX Image

Saturn
HST/OpTIIX

F953N
F467M
F336W



SATURN: Rings close to widest open configuration (Oct 2017 is widest; 30-year-cycle).

OpTIIX Image Simulation assuming:

- 4K x 4K pixels imager with
- 0.05 arcsec/pixel on the sky
- Readout Noise: 15 e- or less
- Quantum Efficiency: >70% from 450 nm to 900 nm

A higher performance instrument could be added later, as OpTIIX is modular.

It will inspire students and amateur astronomers by providing access to OpTIIX for their own exploration

HST WFPC2 Image

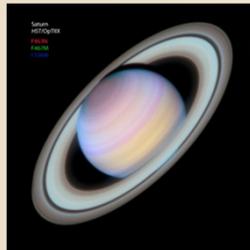




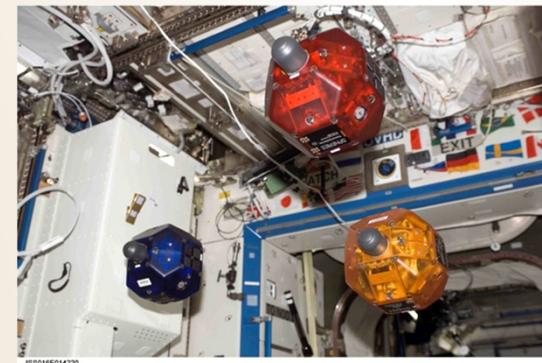
Planned OpTIIX Education and Public Outreach Program (STScI)



- Public engagement through website and other social media.
- Opportunities for amateur observers to propose observations through web based tools. The US has over 2 million amateur astronomers, and many more worldwide.
- Engagement with middle schools and high schools through an observing program similar to the very successful EarthKam program with curriculum materials for teachers to integrate OpTIIX and ISS into the classroom...



- Program for University Students to propose observations and optical control experiments, modeled after the SPHERES project on ISS. Development tools will be built using integrated development environments like MATLAB, as SPHERES has successfully demonstrated.

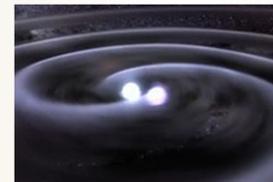
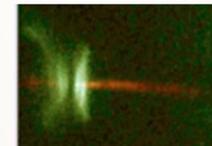
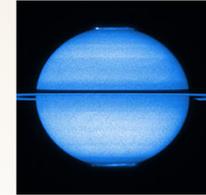




OpTIIX is a Technology Demonstration Project – but some limited science observations may be possible



- **High-cadence monitoring of outer solar system planetary atmospheres.**
- **Stellar population studies of nearby star-forming regions.**
 - Both for Galactic and nearby extragalactic systems (census of Local Group)
- **Imaging of protoplanetary disks.**
 - Spatially resolved observations of edge-on disk candidates to follow-up WISE imaging.
 - Synoptic monitoring of the proplyds in Orion for variability due to accretion events and shadowing of illumination by inner-disk substructures.
- **Dynamics of outflows from young stars.**
 - Time-domain studies of outflows from Young Stellar Objects (YSOs). Currently only a tiny fraction of YSOs have been studied at high cadence.
- **Fast follow-up observations of transient events.**
 - Gamma Ray Bursts. Progenitors of short hard bursts unknown; there are indications of rapid early decay. If the capability to schedule OPTIIX observations within 1 or 2 orbits of notification of event is possible then OPTIIX would have deeper search capability than an 8-m telescope observing no earlier than 12 hours after the burst.
 - Gravitational wave detections. The LIGO and Virgo ground-based gravitational wave detectors will observe the merger of neutron star binaries with a large error box. The fast follow up and high angular resolution available with OpTIIX will allow the study and localization of this event in the optical band, and serve to reject background.





OpTIIX is Well Aligned with the Technology Priorities and Recommendations of the NRC



The OpTIIX Program will significantly advance our ability to assemble the large optical space telescopes required by our most compelling science drivers for the future

- In particular, OpTIIX can enable **technologies critical to the search for life beyond the Earth** as described in the roadmap in “**TA08 Science Instruments, Observatories and Sensor Systems and Technology Development Project Plan for the Advanced Technology Large Aperture Space Telescope (ATLAST)**”, NASA Astrophysics Mission Concept Study (2009)
- OpTIIX will also address major items in “**NASA SPACE TECHNOLOGY ROADMAPS AND PRIORITIES - Restoring NASA’s Technological Edge and Paving the Way for a New Era in Space**”- NRC Report (2012), specifically:
 - **Top Technical Challenges for Technology Objective C: (Table S.2):**
 - **(C2) New Astronomical Telescopes:** Develop a new generation of astronomical telescopes that enable discovery of habitable planets, facilitate advances in solar physics, and enable the study of faint structures around bright objects.....
 - **Highest Priority Technologies for Technology Objective C (Table S.3):**
 - **(X.2) Lightweight and Multifunctional Materials and Structures**
 - **Appendix K-9 – Technology 8.1.3, Optical Systems: ...of particular interest: active wavefront control...**
Because lightweight, actively controlled telescope systems will be challenging to test fully in a one-g environment, low-cost access to space, possibly including use of the ISS, will open key opportunities for maturing the TRL of the technology...



Current Status



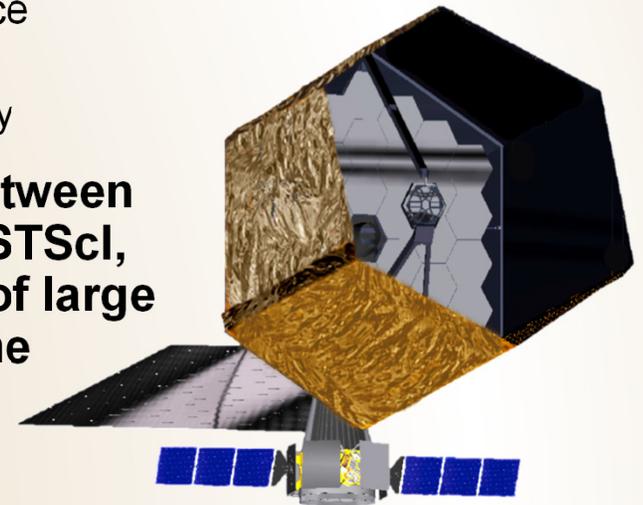
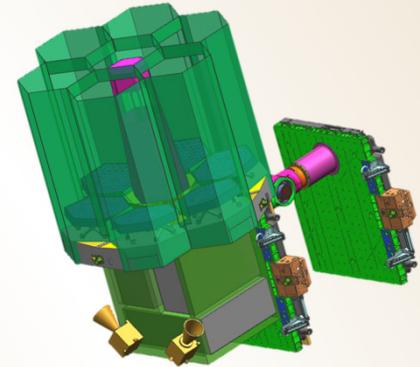
- **Pre-Phase A Concept Study: July – Nov. 2011**
- **Phase A/B: Dec. 2011 – Sept. 2012**
 - Systems Requirement Review on March 20, 2012
 - PDR in Sept. 2012
 - Planning for FY15 launch (in 3 years) and first light, assuming ideal FY12 funding.
- **Accomplishments**
 - Have developed a cost-effective implementation plan consistent with class-D, technology demonstration mission
 - Established mature telescope concept, optical description, and optical interfaces with FGC, WFS&C, Imaging Camera
 - Developed clear ISS interfaces, launch modules and configuration, robotic assembly concepts, feasibility analysis, viewing angles, and operations concept
 - Performed imaging performance & end-to-end performance simulations and analyzed gimbal, pointing and segment control performance
- **Challenges:**
 - Secure FY12 funding for long-lead procurement to protect 2015 launch readiness
 - Secure FY13-15 funding commitment
 - Balance telescope ISS operational performance vs. complexity and cost
 - Pointing stability and image quality vs. gimbal performance
 - Mirror optical stability vs. orbital thermal environment
 - Science utilization requirements vs. low cost, class D, technology demonstration



OpTIIX is a Timely Investment



- **OpTIIX will demonstrate an *affordable* approach to the launch and deployment of large space telescopes by**
 - Integrating substantial NASA & DOD technology investments
 - Leveraging existing ISS facilities and robotics
 - Bringing together, for the first time, fully active telescope technologies and in-space assembly & upgrade capabilities
- **OpTIIX operating on ISS by mid-decade will**
 - Advance the timescale for many kinds of ambitious space science missions by at least 10 years through major reductions in cost & risk
 - Demonstrate technologies identified in NRC's ASTRO2010
 - Be a centerpiece of an HEOMD/SMD/OCT collaboration providing high value, visibility and engagement with a large audience
 - Involving both the public & the science community
 - At a key time: 2015+, in advance of the 2020 Decadal Survey
- **OpTIIX is an effective and efficient collaboration between multiple NASA Centers (JPL, JSC, and GSFC) and STScI, which will significantly accelerate the deployment of large optical systems in space and the performance of the science enabled by such facilities**





Backup Slides

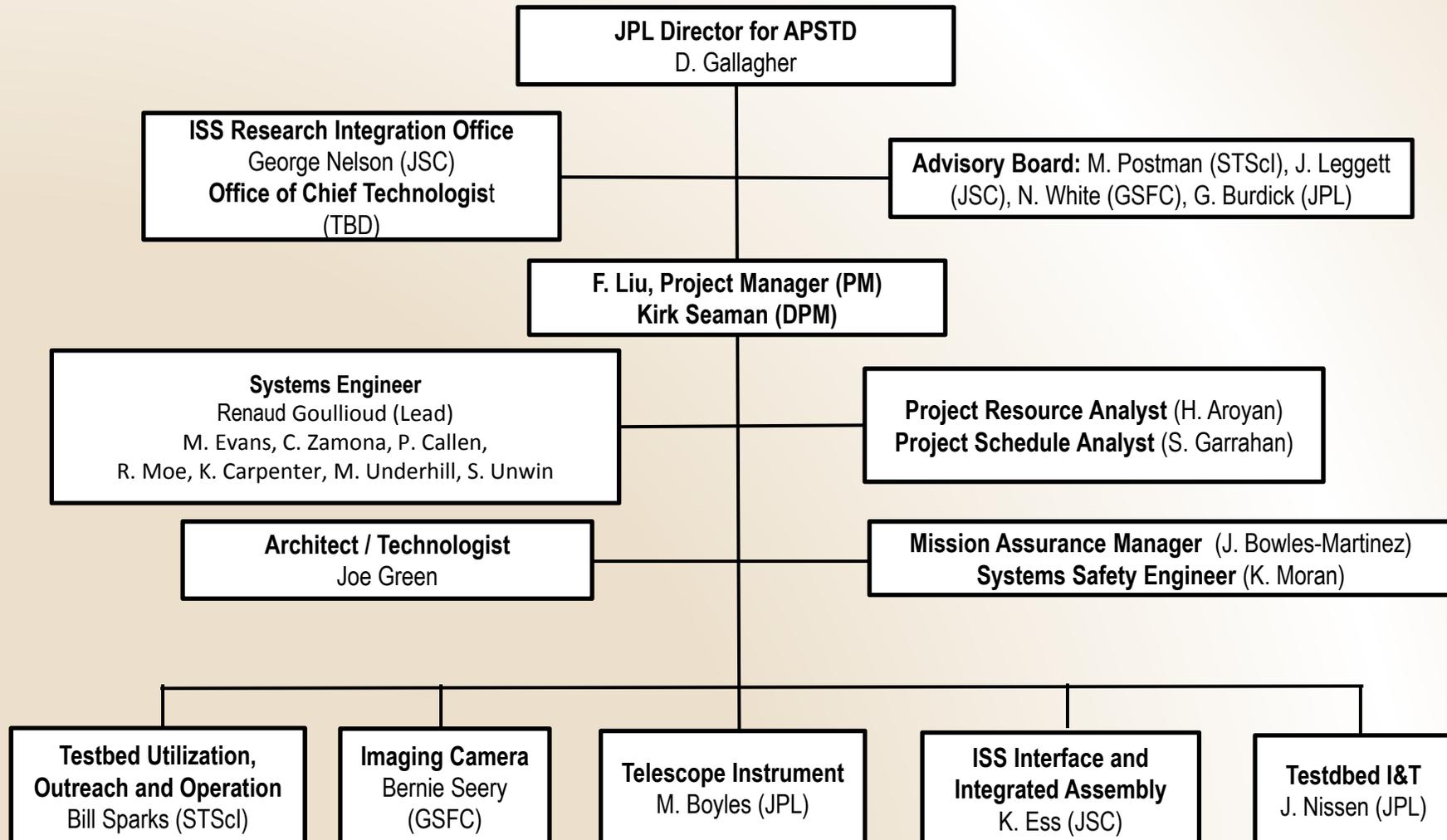


The OpTIIX Team and Schedule



Organization of the OpTIIX Team

OpTIIX Org. Chart,
2/21/2012





The OpTIIX Team

Institutional Strengths Leveraged



JPL Jet Propulsion Laboratory

- ★ Technologies for next generation space telescopes
- ★ Next generation telescope optical design and control
- ★ Systems engineering
- ★ Project management

Johnson Space Center

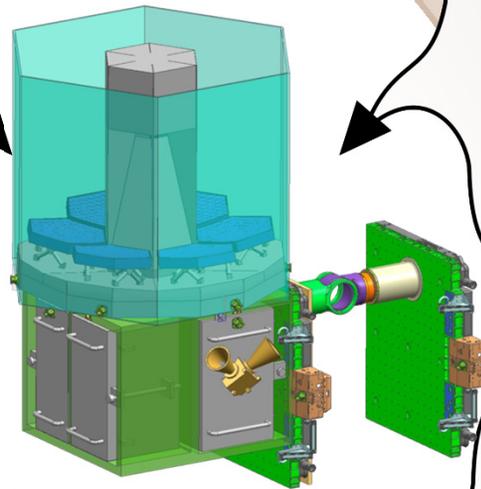
- ★ Understanding of human space flight
- ★ Knowledge of the ISS
- ★ Real time telerobotic operations on ISS
- ★ Design/ development of robotic actuators and controls
- ★ Systems engineering

Goddard Space Flight Center

- ★ Imaging instrument development
- ★ On-orbit servicing and upgrade
- ★ Systems engineering
- ★ Membership on optics, thermal, requirements, etc. teams

Space Telescope Science Institute Operated for NASA by AURA

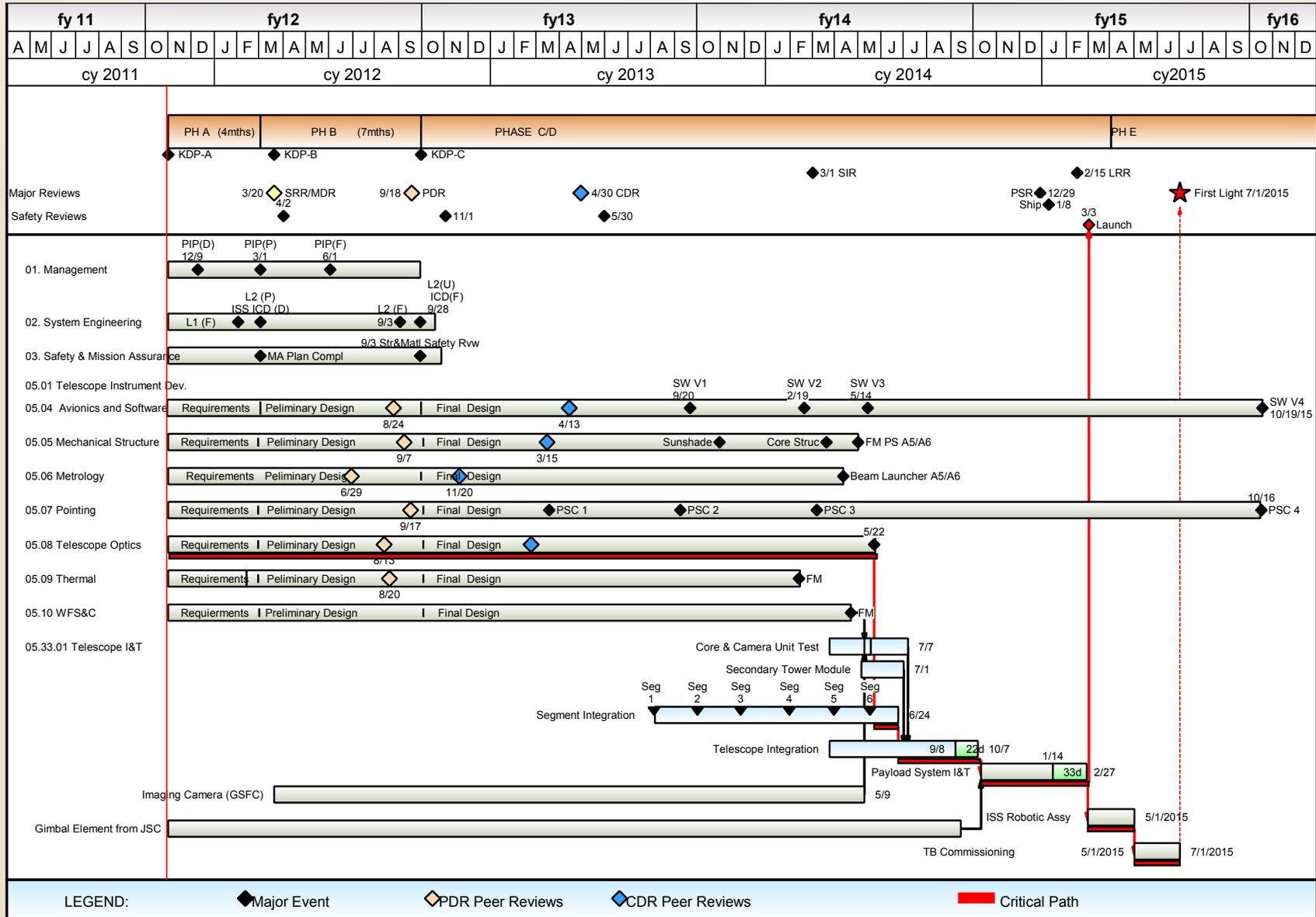
- ★ Management / operation of space telescopes
- ★ Tools/infrastructure for space astronomy public engagement
- ★ Advanced image processing



OpTIIX



Summary Schedule





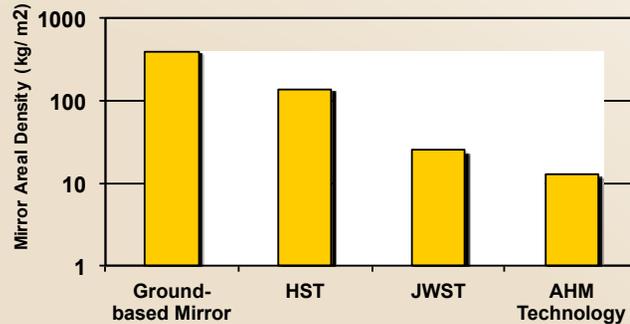
Key Technologies

Key Technologies Needed for Next Generation UV-Optical-NIR Space Telescopes



Lightweight Mirrors

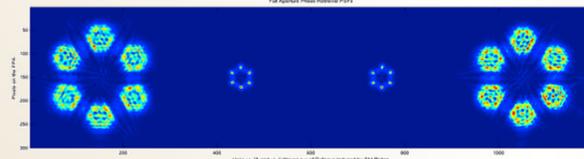
- Lower Areal Density lowers cost
- SiC-based Actuated Hybrid Mirrors (AHMs) lower the mass and cost for future very large space telescopes



How much would an 8-m mirror weigh?

VLT	HST	JWST	AMT
20,000 kg	7,000 kg	1,250 kg	650 kg

Active Wavefront Control is also essential



On-orbit assembly and servicing

- On-orbit assembly in conjunction with an active optical system, allows reduced I&T time and cost on the ground because mechanical and optical errors can be corrected on-orbit.



Tele-robotic observatory assembly and servicing in space



Mirror Material Options and Cost for an 8-meter Telescope



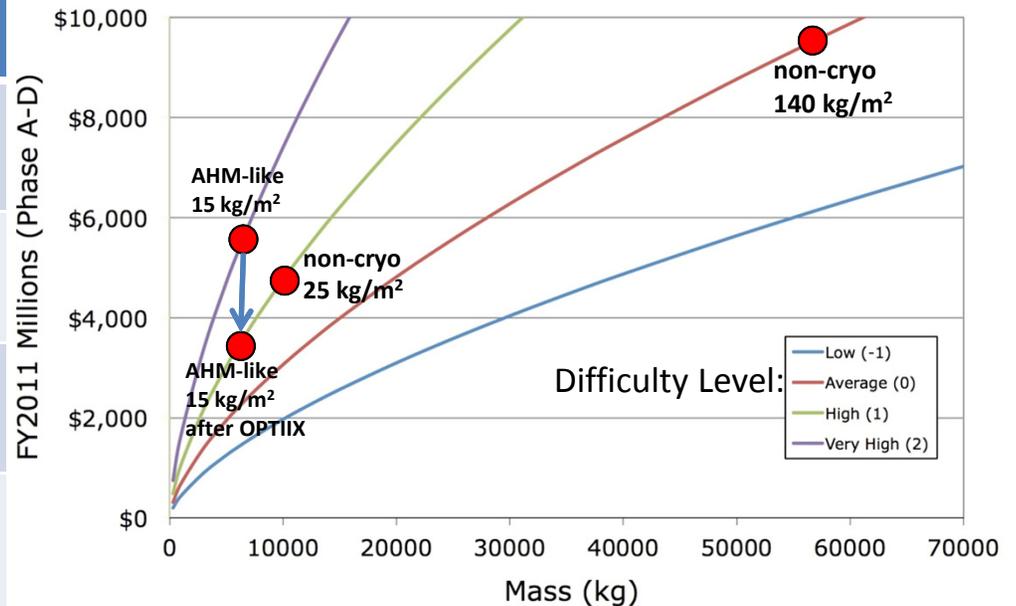
Mirror Material	Tech. Basis	Mirror Areal Density (kg/m ²)	Mass of 8-meter primary mirror (kg)	Total Space Observatory Mass** (mT)	Thermal Control (CTE/Diffusivity)
ULE Glass	Gemini, VLT	400	20,000	167	0.033
Light-weighted ULE Glass	HST	140	7,000	58	0.033
Light-weighted Beryllium	JWST	25	1,250	10	0.19
SiC or SiC-based Nano-laminate AHM	OpTIIX and Future UVOIR missions	15	750	6.3	0.038

**Assuming a mirror-to-observatory mass ratio of 0.12 (like JWST)

SiC stiffness permits an open-back design, which coupled with good emissivity and high diffusivity, enables efficient thermal control.

Estimated Phase A-D Cost of Future 8-meter Telescope

$$\text{FY11 Cost} = \$3.06\text{B} (\text{Mass}/10,000 \text{ kg})^{0.654} \times (1.555)^{\text{Difficulty Level}} \times (N^{-0.406})$$



While several possible mirror materials could be used to build an 8-m class UVOIR space telescope, the decision point comes down ultimately to cost considerations.

Mirror technology improvements do have a significant impact on mission cost – they reduce them significantly for a given aperture size.



Mirror Material Options and Cost for a 3-meter Telescope



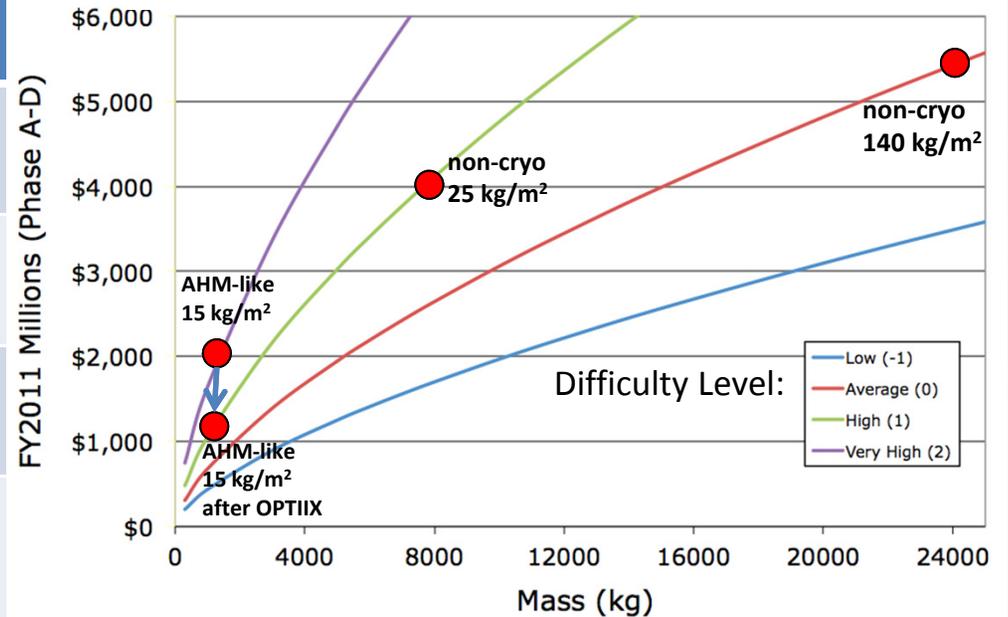
Mirror Material	Tech. Basis	Mirror Areal Density (kg/m ²)	Mass of 3-meter primary mirror (kg)	Total Space Observatory Mass** (mT)	Thermal Control (CTE/Diffusivity)
ULE Glass	Gemini, VLT	400	2,800	24	0.033
Light-weighted ULE Glass	HST	140	990	8	0.033
Light-weighted Beryllium	JWST	25	177	1.5	0.19
SiC or SiC-based Nano-laminate AHM	OpTIIX and Future UVOIR missions	15	106	0.9	0.038

**Assuming a mirror-to-observatory mass ratio of 0.12 (like JWST)

SiC stiffness permits an open-back design, which coupled with good emissivity and high diffusivity, enables efficient thermal control.

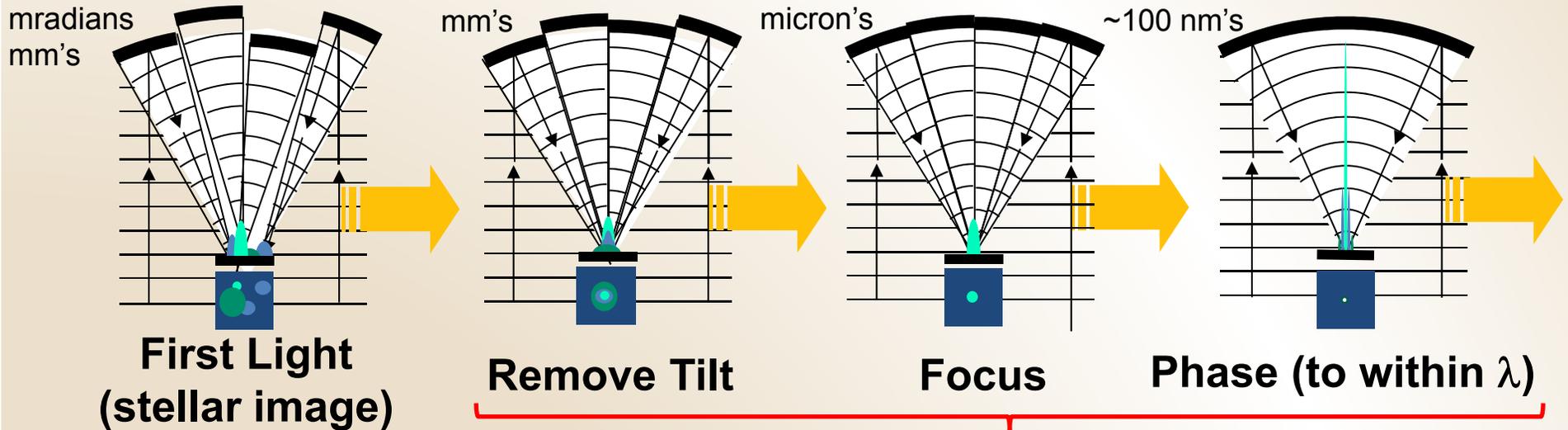
Estimated Phase A-D Cost of Future 3-meter Telescope

$$\text{FY11 Cost} = \$3.06\text{B} (\text{Mass}/10,000 \text{ kg})^{0.654} \times (1.555)^{\text{Difficulty Level}} \times (N^{-0.406})$$

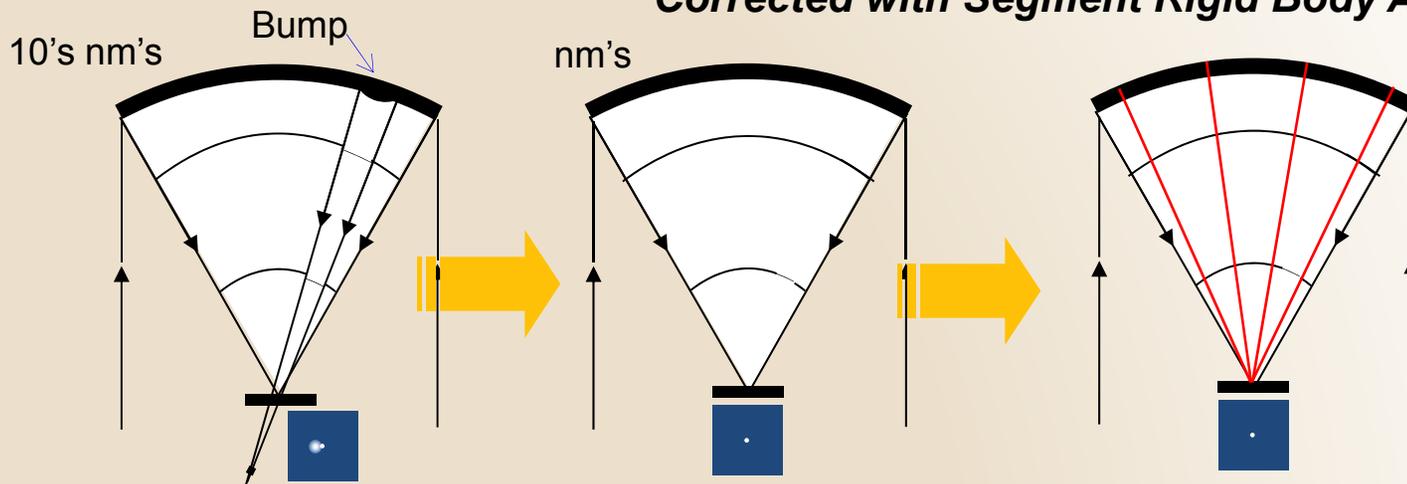


Mirror technology improvements do have a significant impact on mission cost – they reduce them significantly for ANY given aperture size.

Active Control of a Segmented Space Telescope



Corrected with Segment Rigid Body Actuators



Corrected with Segment Shape Actuators

Laser metrology truss measures, locks up and monitors the alignment to nm's. The telescope can now be pointed away from the calibration star and image other scenes.

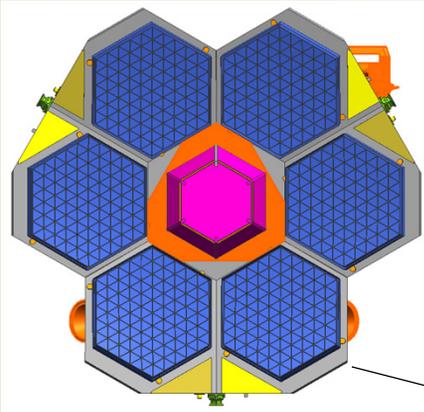


Design Illustrations

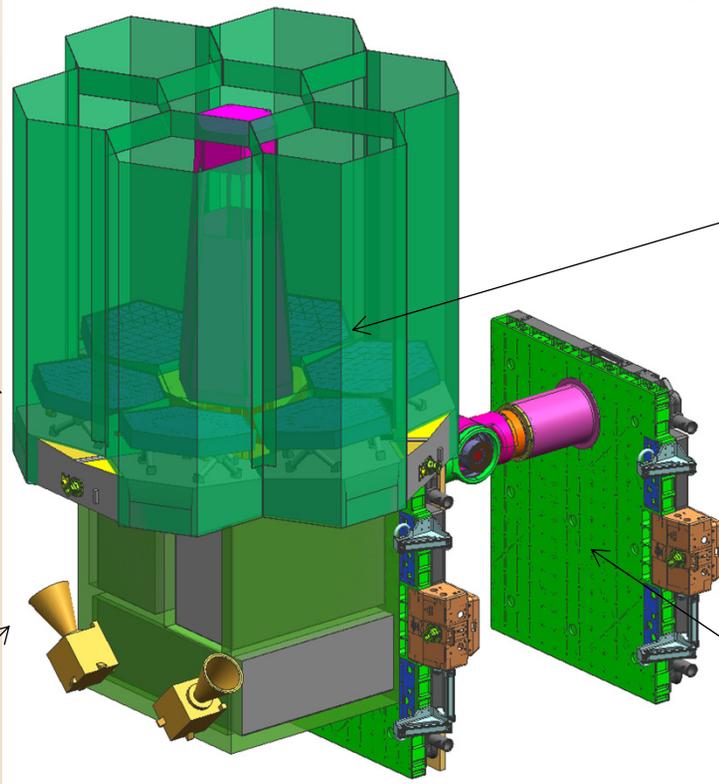
OpTIIX System Configuration



Orbital upgradable items: primary mirror segment pairs, gimbal, imaging camera.

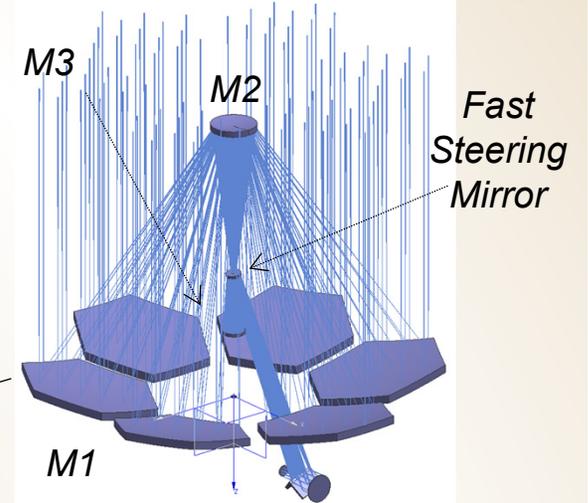


1.45m aperture
50cm point to point
segments
assembled on orbit

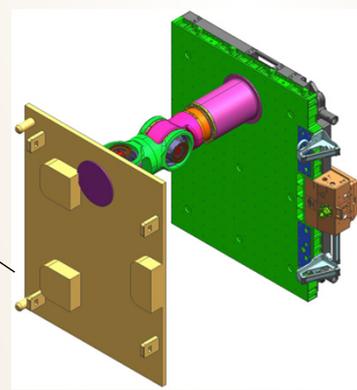


Telescope Core Module

- Imaging camera (GSFC)
- Wavefront Sensing cameras
- Laser metrology and control
- Electronics, power, command & telemetry
- Pointing control & thermal control



Three-Mirror Anastigmat Telescope

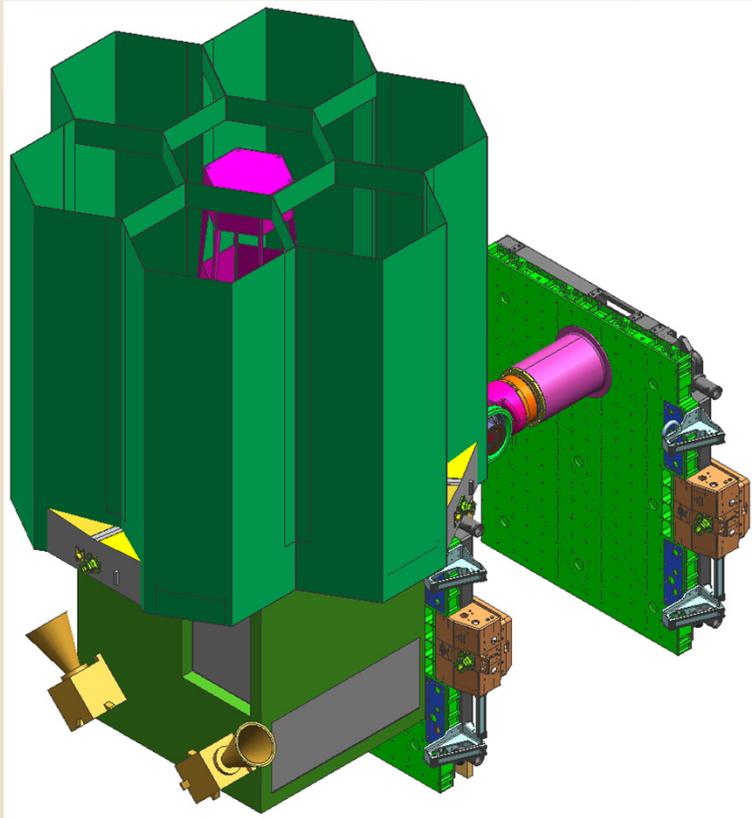


3-axis gimbal (JSC), attached to the Instrument Module on orbit; FRAM I/F on each end

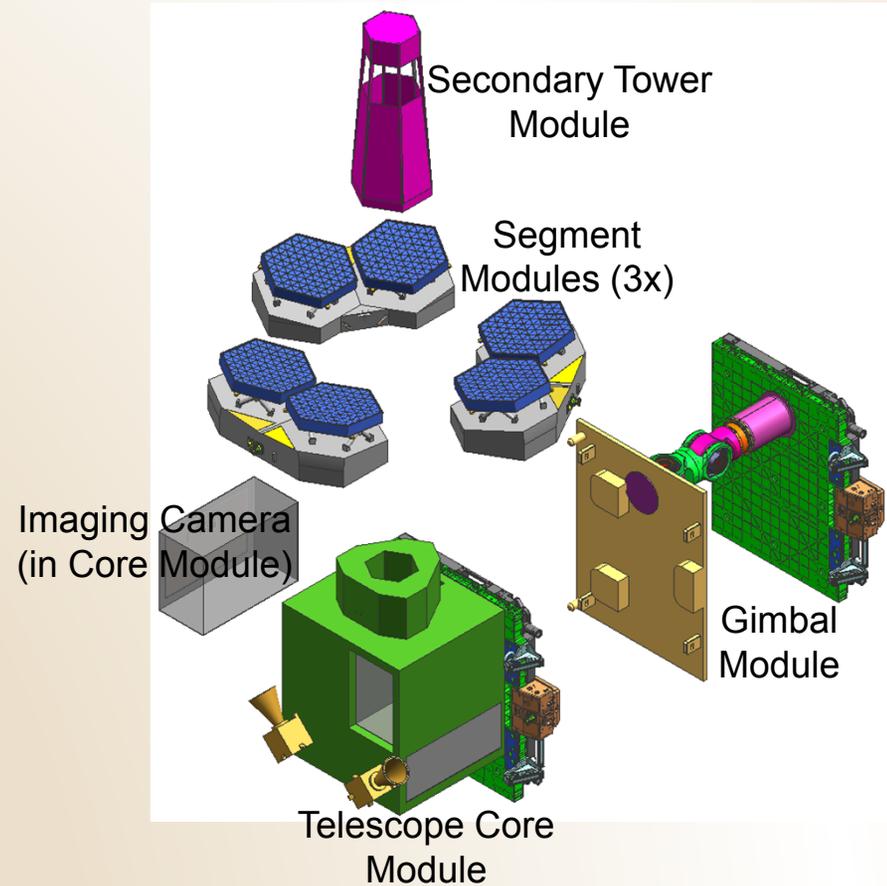
Payload Configuration



Assembled Configuration



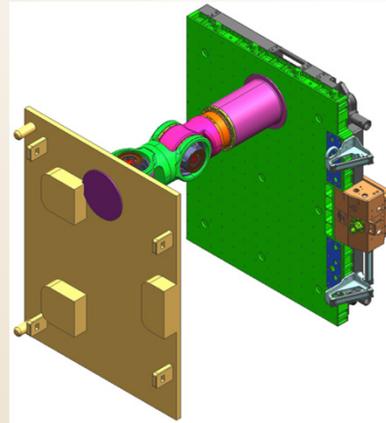
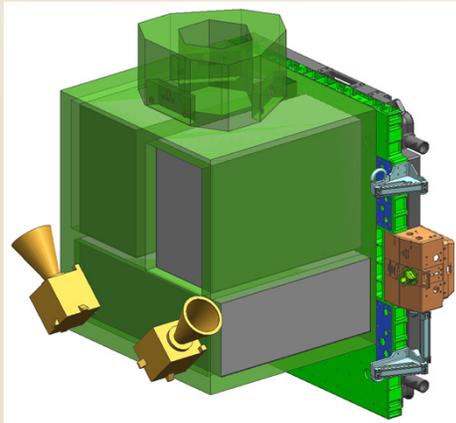
Launch Configuration



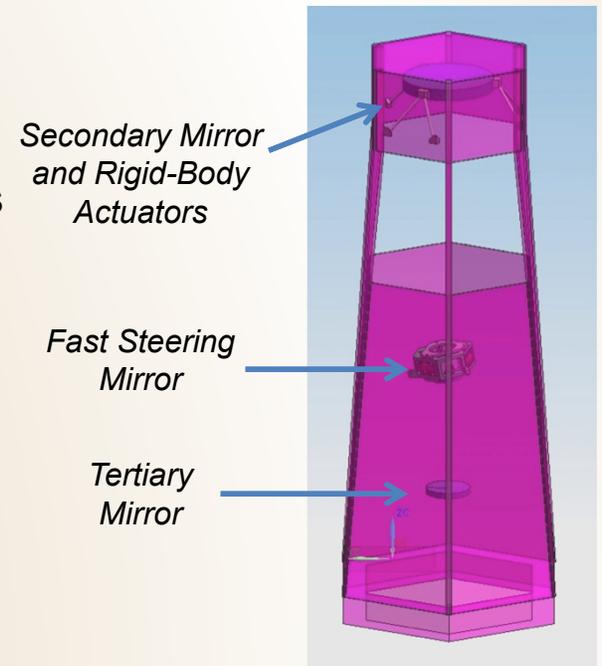
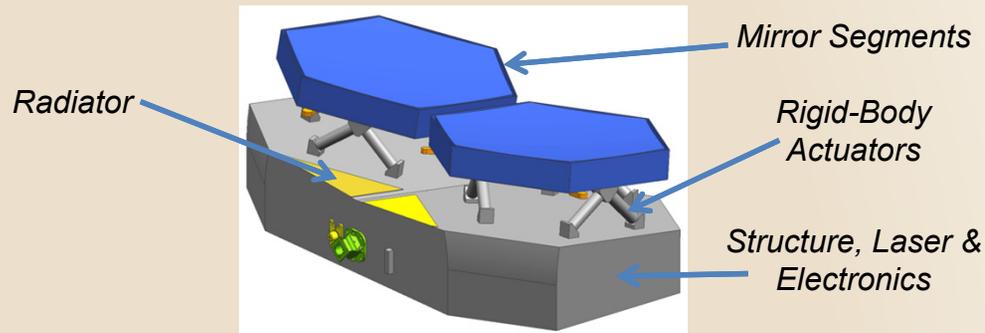
Launch Segments



- Exposed (un-pressurized) launch segments
 - Telescope Core Module;
 - Gimbal Module (JSC)



- Pressurized launch segments
 - Secondary Tower Module; Primary Segment Modules
 - Deployable Sunshade



OpTIIX Gimbal System



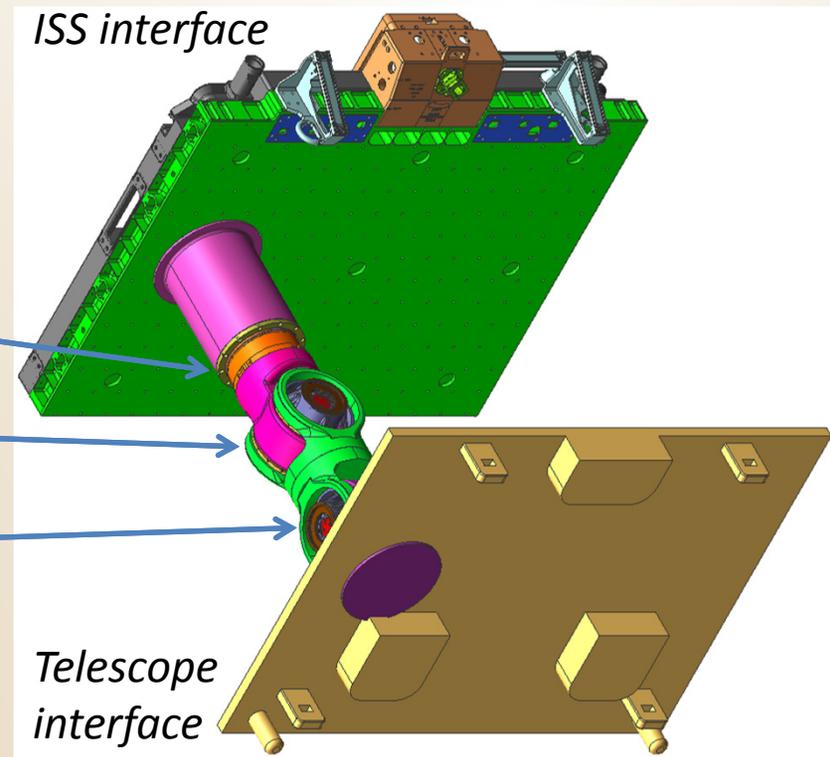
The OpTIIX Gimbal design will leverage existing Robonaut2 joint designs to minimize engineering development.

Scaled in proportion to meet the performance requirements for:

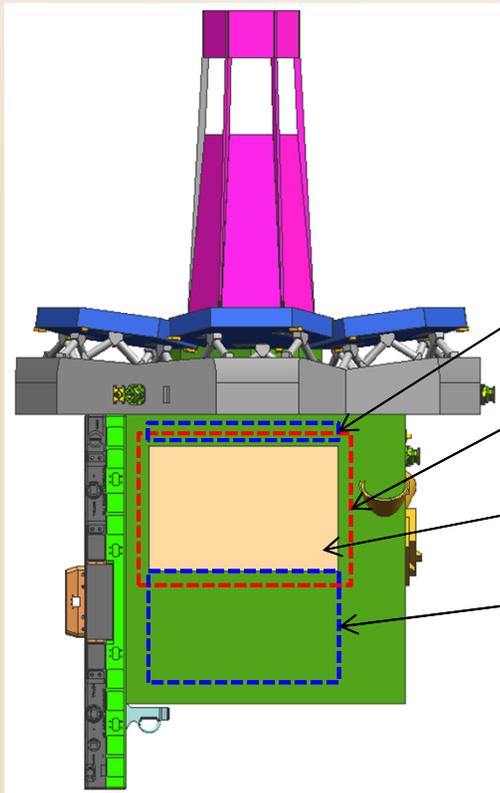
- mass and power
- rotational rates
- range of motion
- stiffness

Three degrees of freedom:

- Azimuth (± 90 degrees)
- Elevation (± 20 / -45 degrees)
- Field Rotation (± 20 degrees)



OpTIIX Imaging Camera Configuration



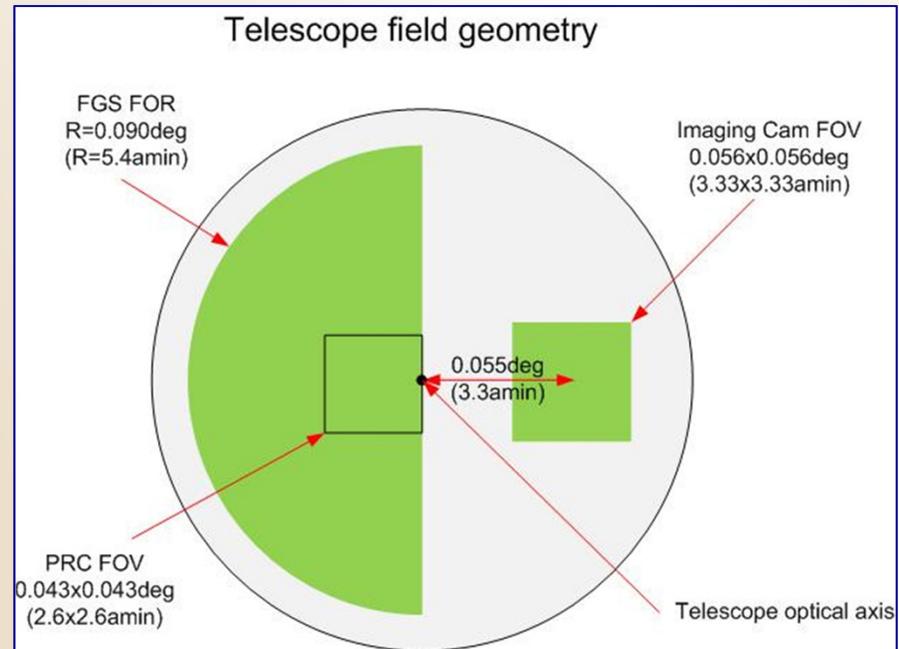
Latch system volume boundary

Imaging Camera volume boundary
[Insertion direction into page]

Radiator area

Radiator area extension TBD

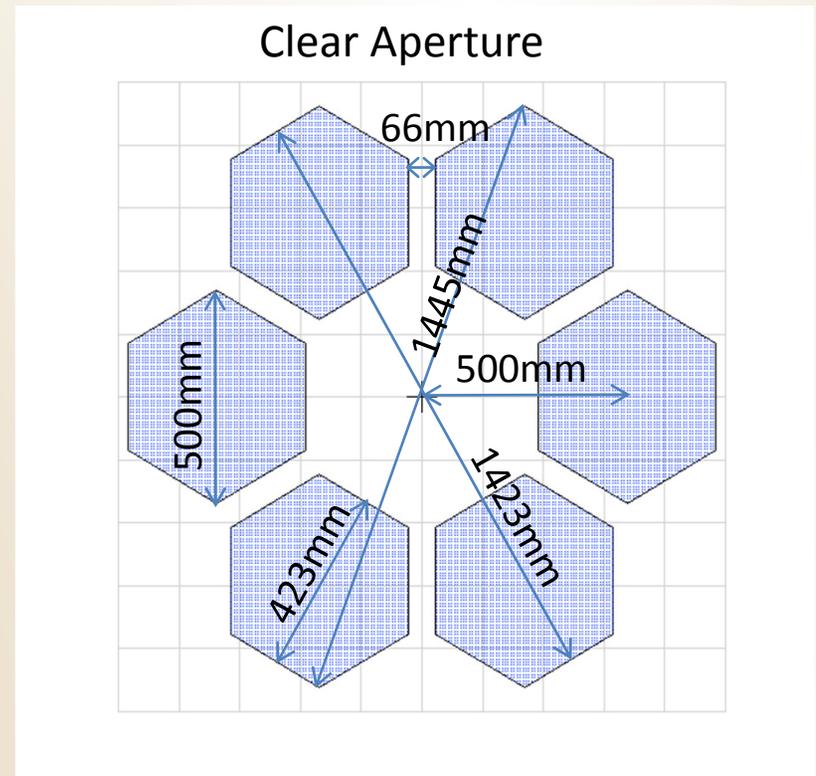
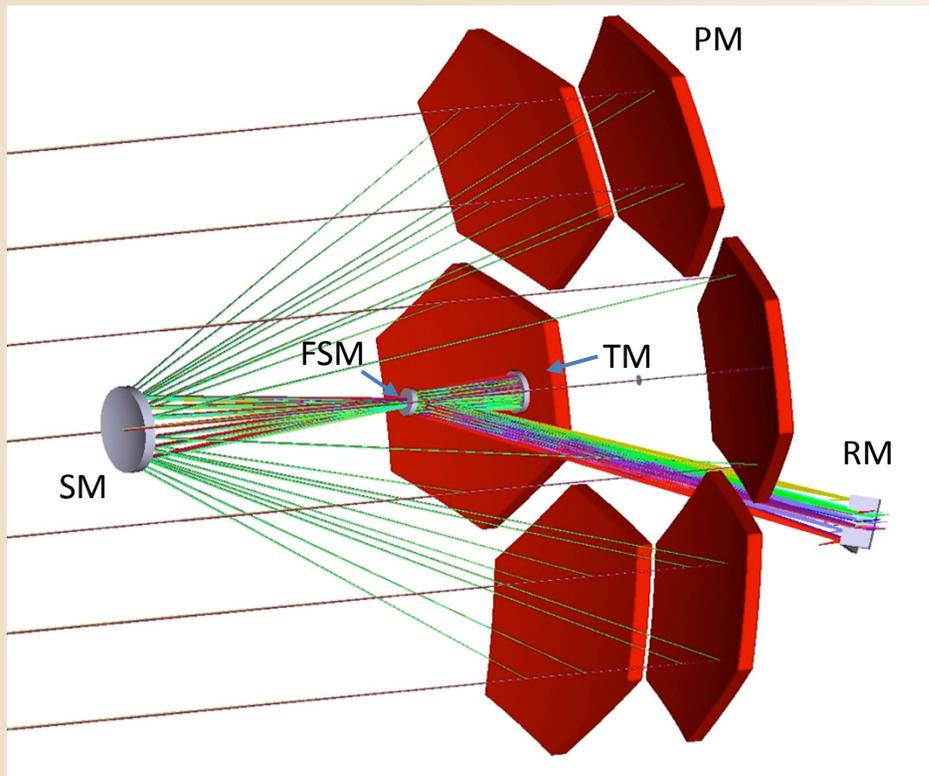
Location of the IC in Core Structure



Telescope



- The front-end telescope is an on-axis Three-Mirror Anastigmat (TMA) configuration.
- The three mirrors with optical power (PM, SM, TM) are conic aspheres.
- The PM is made up of six hexagonal segments and defines the entrance pupil.
- The FSM is located at the real-image pupil.

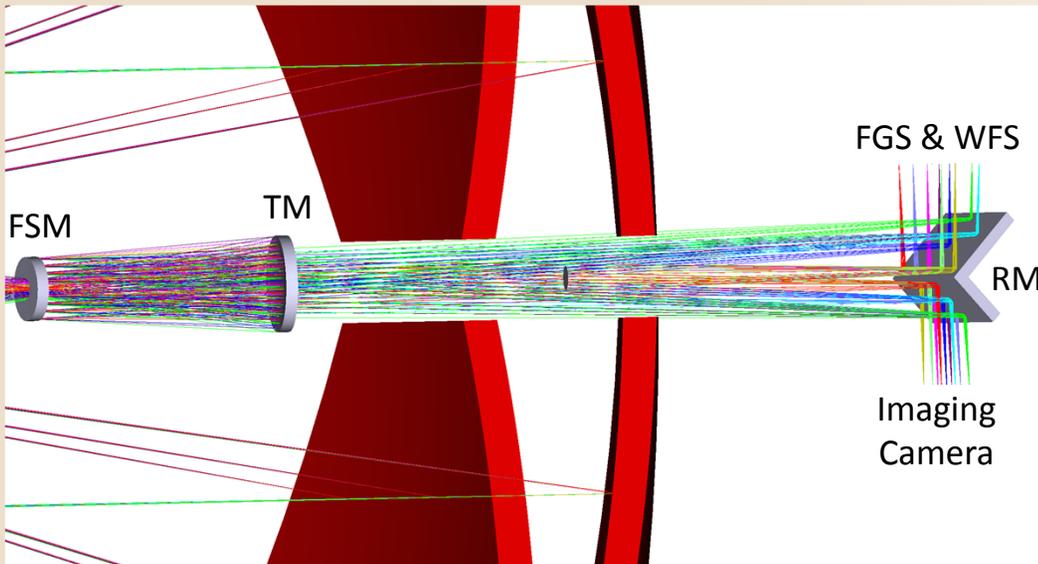
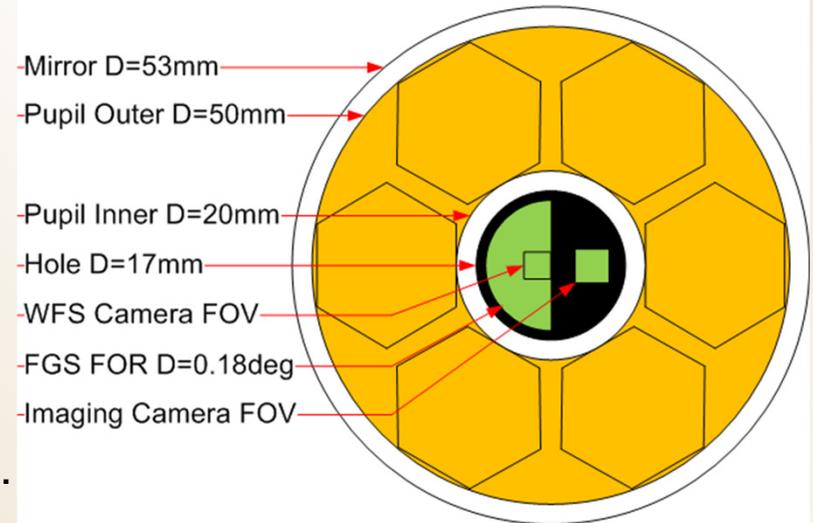


Field of View

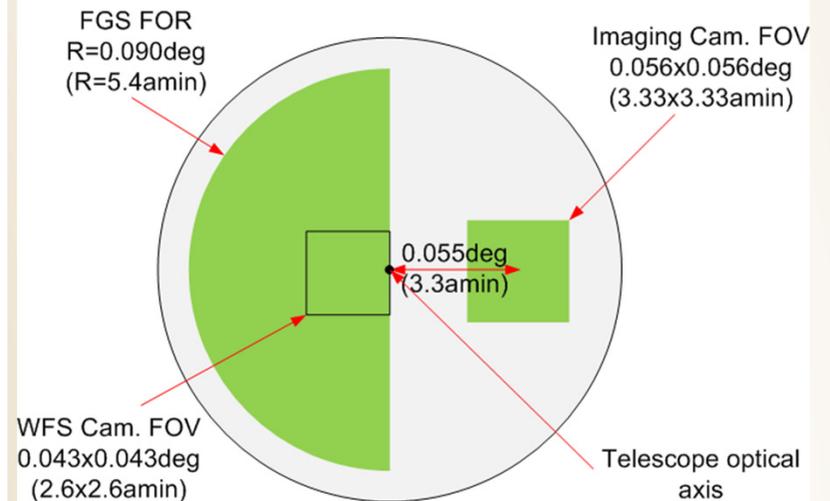


- The FSM has a hole in it to let the optical beam go through from the SM to TM.
- The FSM hole is located at the telescope intermediate focus.
- The size of the hole limits the FOV of the system.
- The Roof-top Mirror (RM) folds the optical beam toward the Imaging and WFS cameras.

Footprint on the Fast Steering Mirror



Telescope field geometry



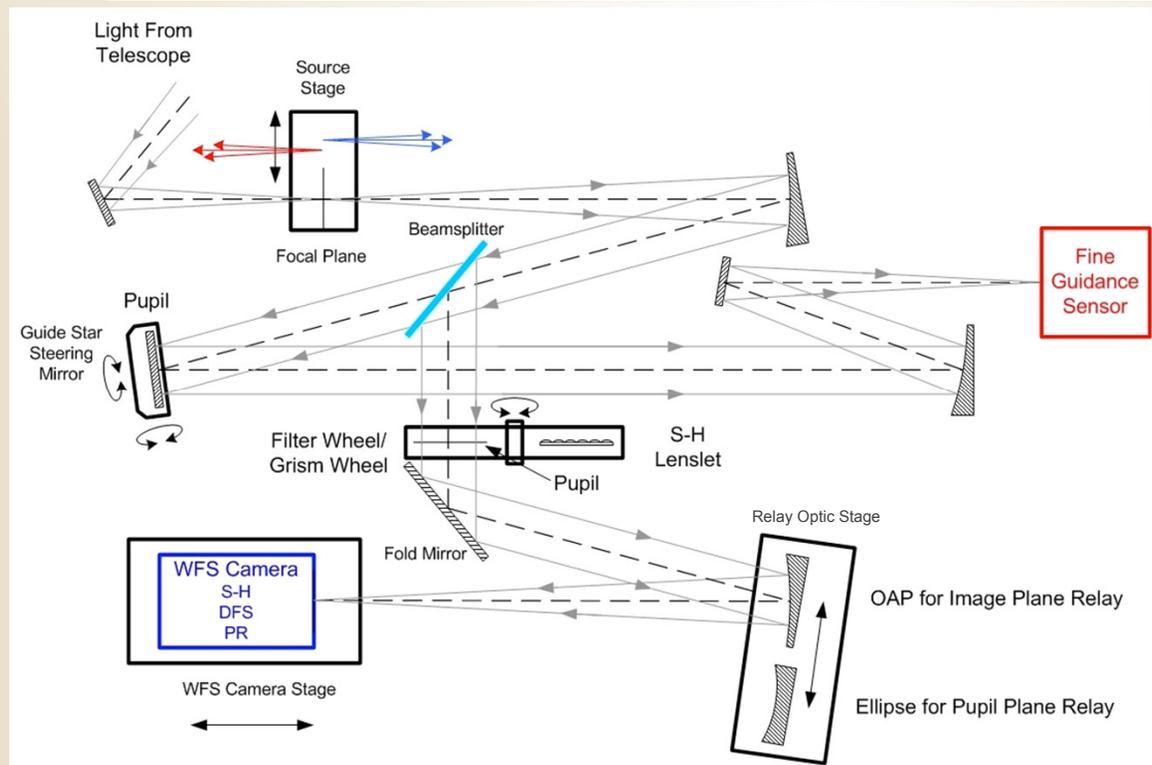
Wavefront Sensing Camera Unit



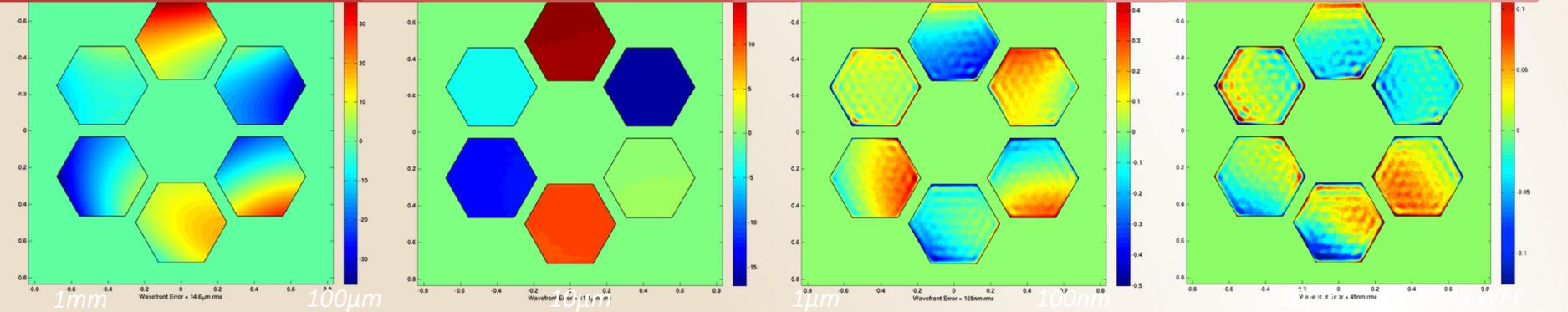
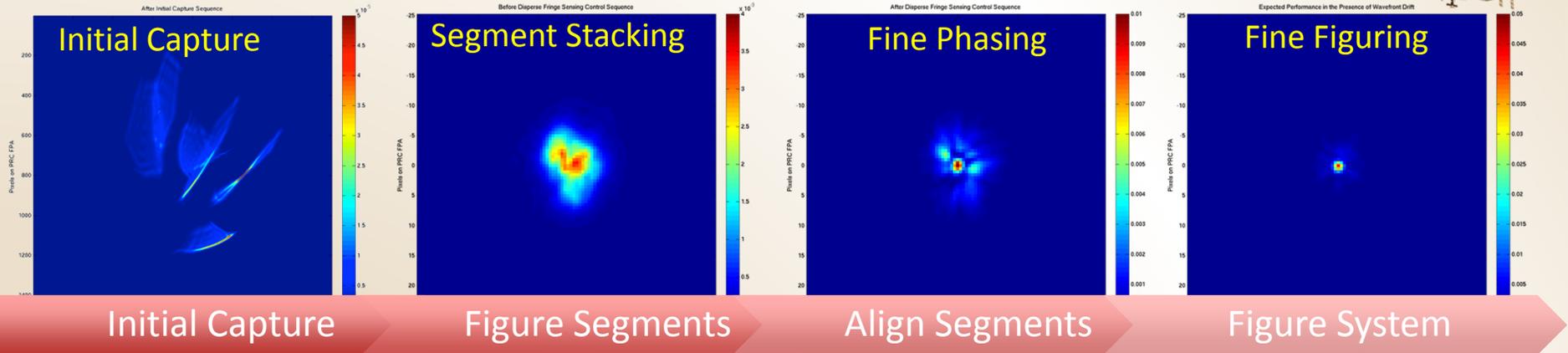
WFS Camera Features

- *Fine Guidance Camera (FGS)*
 - Steerable mirror for Guide Star acquisition
 - Fast detector for 1kHz pointing error estimation
- *Wavefront Sensing Camera (WFS)*
 - Shack-Hartmann Sensing for initial segment alignment
 - Dispersed Fringe Sensing for segment co-phasing
 - Phase-Retrieval Sensing for fine wavefront adjustment
 - Performs 80% Strehl ratio demonstration using narrow-band filter

Wavefront Sensing	Control Objective
Rigid-Body Actuator Encoders	Capture Segment Alignments
Shack-Hartmann Sensing	Segment Tilt and Figure
Dispersed Fringe Sensing	Segment Piston
Phase Retrieval	Total System Correction
Laser Metrology	Maintain Alignment



Wave Front Sensing and Control



Shack-Hartman

Dispersed Fringe Sensing

Phase Retrieval

