UVOIR Space Astronomy for the Coming Decades

The Advanced Technology Large-Aperture Space Telescope (ATLAST)

Carl Stahle

New Business Lead for Instrument Systems and Technology

Harley Thronson

Senior Scientist for Advanced Astrophysics Concepts

NASA Goddard Space Flight Center

And the ATLAST Technology Team

Joint COPAG and ExoPAG Meeting

224th American Astronomical Society Meeting

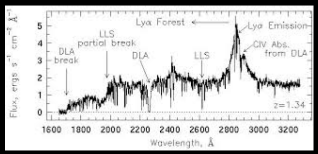
June 5, 2014

The ATLAST Technology Team

Carl Stahle (Chair, GSFC)
K. Balasubramanian (JPL)
Matthew Bolcar (GSFC)
Mark Clampin (GSFC)
Julie Crooke (GSFC)
Lee Feinberg (GSFC)
Kathy Hartman (GSFC)
Gary Mosier (GSFC)
Manuel Quijada (GSFC)
Bernard Rauscher (GSFC)
David Redding (JPL)
Norman Rioux (GSFC)
Stuart Shaklan (JPL)
Phil Stahl (MSFC)
Harley Thronson (GSFC)

Developing a Shared Vision

Cosmic Birth



- Broad instrument suite
- Sensitivity down to ~1000 Angstroms

Both

- Large aperture
- Diffraction limited
- UV, Optical & NIR

Living Earths

- Coronagraph or starshade
- Superb mirror stability

Science Requirements Determine Observatory Parameters

- **The ATLAST Engineering Reference Design Mission for *Cosmic Birth to Living Earths***
- **Driving requirements**
  - Large aperture: a *10 meter-class space telescope*
  - Diffraction limited, with outstanding wavefront stability
  - Starlight suppression via coronagraph or/and starshade
  - UV to NIR with a wide range of notional instrumentation

ATLAST Requirements from Science Drivers to date

Telescope Parameter	Consensus Value
Primary mirror diameter	≥ 8 meters
UV Sensitivity	(900 Å) 1100 Å – 3000 Å
Vis / NIR Sensitivity	0.3 μm – 2.5 μm (8 μm)
Pointing stability	~1.3 – 1.6 mas
WFE:	
General Astrophysics	Diffraction limited at 0.5 μm (~35 nm WFE)
Exoplanet Observations	~0.01 nm WF stability over ~600 sec (w/ actively controlled coronagraph)

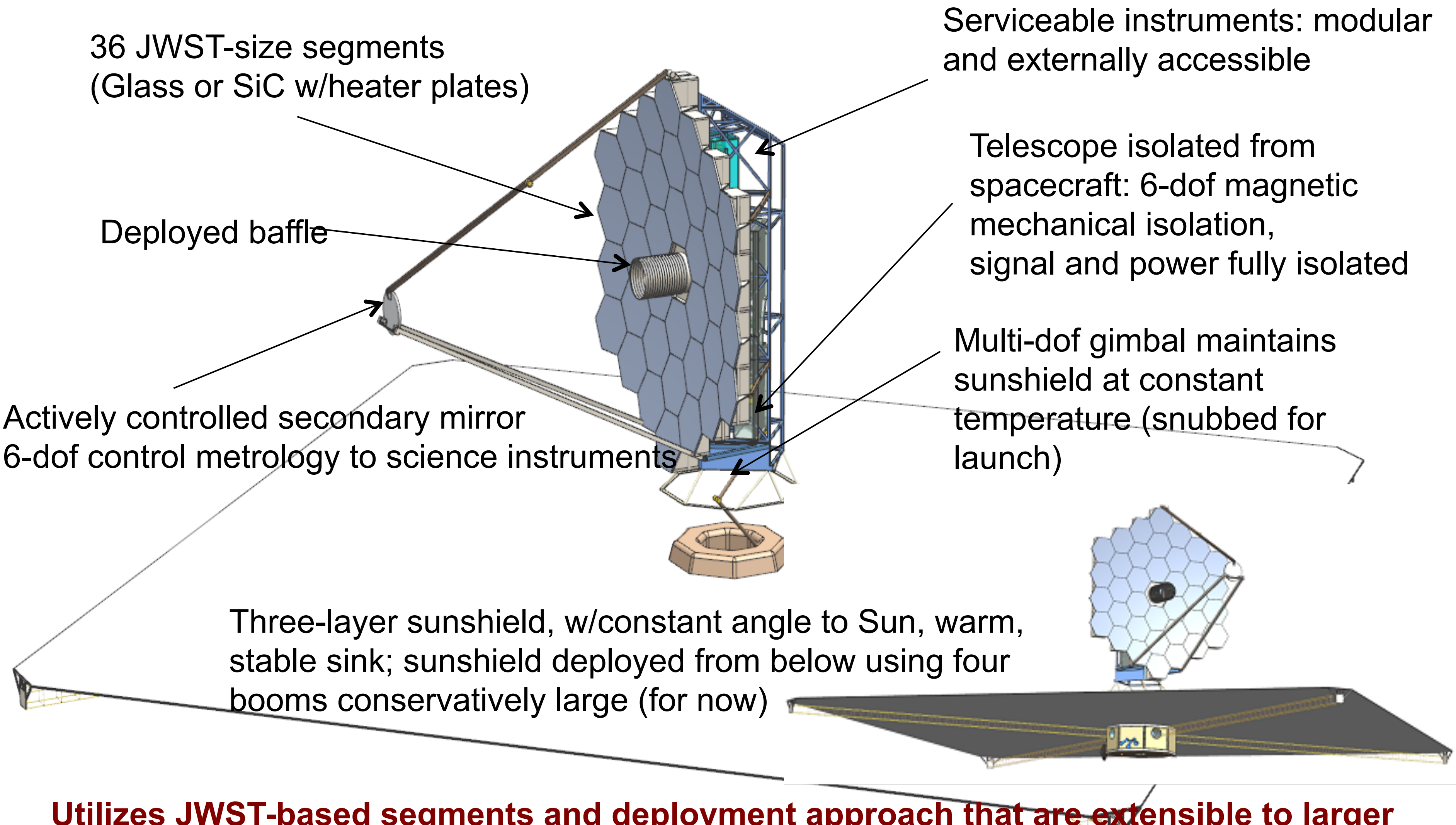
Instrument Parameters	Consensus Value
Starlight suppression	10^{-10} down to IWA ~40 mas
UV Spectroscopy	R = 20,000 – 150,000
Exoplanet Spectroscopy	R = 70 - 500
Vis / NIR Imaging	FOV: 4 – 8 arcmin, Nyquist
UV Imaging	FOV: ~1-2 arcmin

Grey values are stretch goals

- **Approach: build on experience**
  - JWST deployment system, WF sensing and control – but no cryogenic systems
  - Serviceable on orbit
  - Segmented architecture using technologies developed by NASA and others
    - Extensible to other aperture sizes

Notional 10 m-Class Architecture

Deployed Configuration

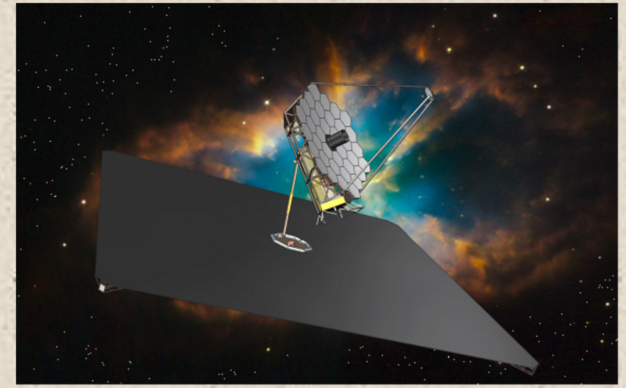


Utilizes JWST-based segments and deployment approach that are extensible to larger (e.g., Falcon 9-H or SLS) launch vehicles. Identified technologies are applicable to a range of apertures.

Technology Investments

Using the reference design for ATLAST, technology investments in five areas will enable all concepts for an observatory capable of vastly exceeding the scientific capabilities of HST, including the ability to search for the spectroscopic signatures of life in nearby Earth-like worlds:

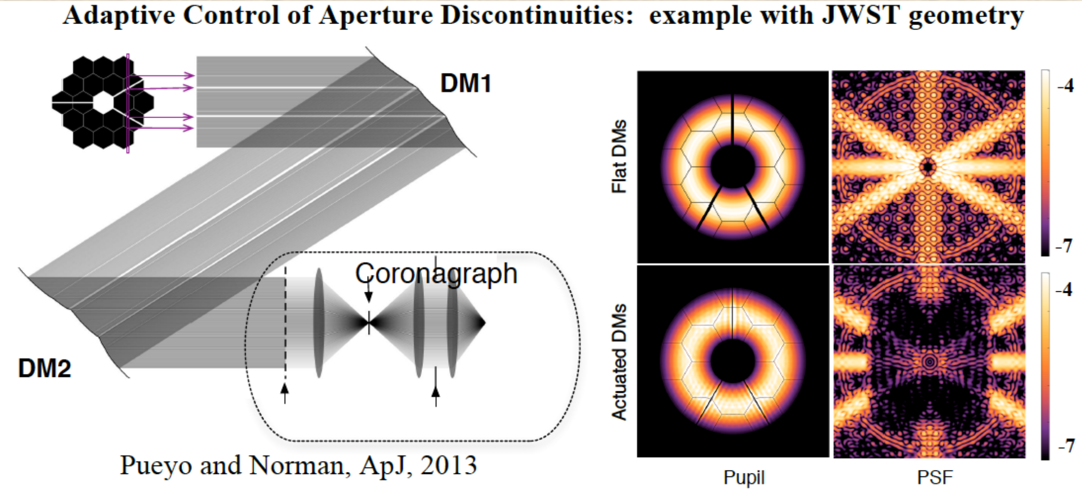
- Starlight suppression system
- Telescope mechanical isolation system
- Active optical system
- Detectors
- Mirror coatings



Starlight Suppression System

- Key Challenges
  - 10^{-10} raw image contrast; 10^{-11} contrast stability
  - Compatible with segmented aperture geometry
  - 40 mas inner working angle
  - Broad bandpass

- Approach
  - Develop both internal coronagraph and starshade
  - Identify technologies that relax stability requirements on telescope
  - Test coronagraphs on a vacuum segmented-aperture testbed



Telescope Mechanical Isolation System

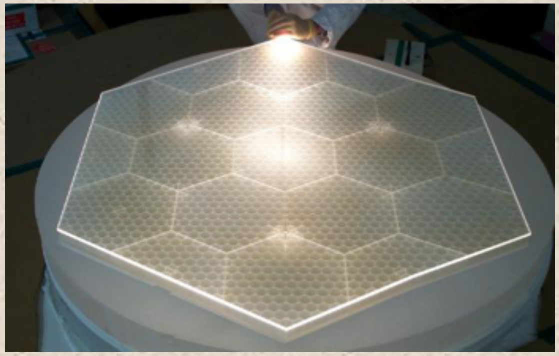
- Key Challenges
  - Line-of-sight pointing stability of 0.1-1.0 milliarcsec
  - System wavefront stability < 0.01 nm (TBR)
  - Total system vibration isolation of 140 dB (assuming JWST-like scaling)
  - Vibration-isolated mass of 5000 kg or more

- Approach
  - Develop system-integrated vibration isolation technologies for telescope
  - Establish capability to model/test vibration effects on segmented optics
  - Close partnership with industry
  - Examples: active and passive damping systems, reaction wheels, tuned mass dampers, magnetic isolators

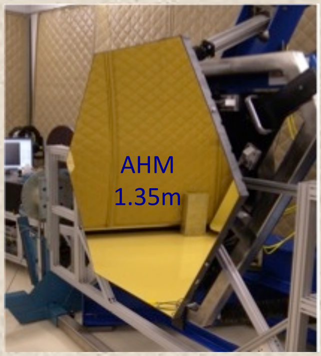
Reference: Feinberg et al., to be submitted to SPIE, Montreal, 2014.

Active Optical System

- Key Challenges
  - Diffraction-limited optical quality
  - Wavefront stability to 10 pm per 10 min
  - UV compatibility (microroughness, contamination)
  - Low cost, low mass, and rapid fabrication
- Approach
  - Optical system design and modeling
  - Segmented mirror system development
  - Active thermal control for stability
  - System-level vibration damping and isolation
  - High-precision actuation



MMSD Lightweight ULE Segment Substrate



AHM SiC-based Segment Substrate

Detectors

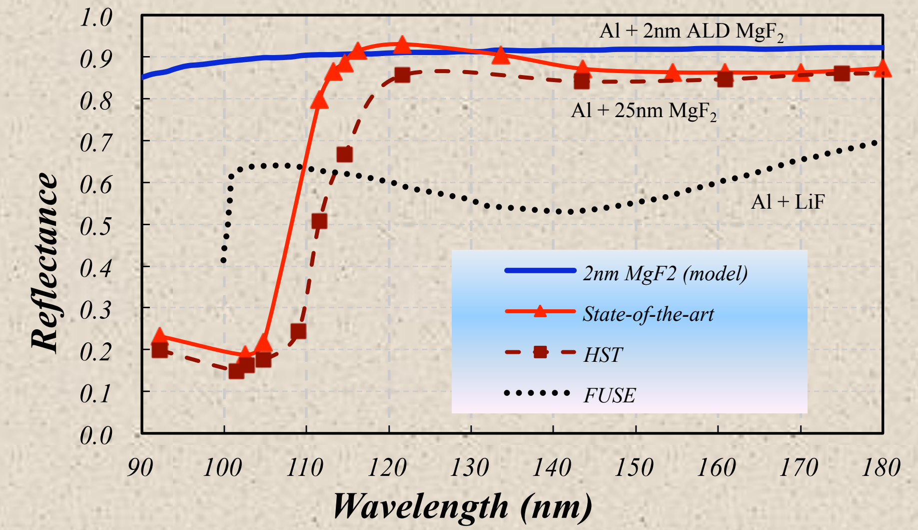
- Key Challenges
  - Visible-blind, high quantum efficiency (> 50%) UV arrays
  - Photon counting visible and NIR arrays
    - Coronagraphic spectroscopy for biosignature characterization
      - Read noise < 1 e- and dark current < 0.004 e-/s/pix
    - Starlight wavefront sensing and control
  - Deep full wells with low persistence and radiation tolerance to enable transit imaging and spectroscopy at all wavelengths

- Approach
  - Parallel development on a family of detectors: UV/Vis/NIR
  - Build on detector accomplishments of HST, JWST, and WFIRST-AFTA
  - Encourage innovative partnerships (university/industry/government)

Mirror Coatings

- Key Challenges
  - High reflectivity (> 90%) coatings to support starlight suppression and high-throughput UV observations
  - High uniformity (< 1%); large spectral range; low polarization (< 1%)
  - Scaling up coatings to large diameter (meters) mirror substrates

- Approach
  - Develop conventional technologies such as physical vapor deposition
  - Develop new coating technologies such as atomic layer deposition (ALD)



Traceability to Cosmic Origins and Exoplanet Exploration Program Office Technology Needs

- Cosmic Origins (Program Annual Technology Report 2013)
  - High-QE, large-format UV detectors
  - High-reflectivity UV coatings
  - Deployable lightweight precision mirrors for future very large-aperture UV/Visible/Near-IR telescope
  - Very large-format, low-noise Visible/IR detector arrays
  - Photon-counting Visible/IR detector arrays
  - High-efficiency UV multi-object spectrometers

- Exoplanet Exploration (Technology Plan Appendix: 2013)
  - Coronagraph
  - Starshade

Path Forward

We welcome your feedback

ATLAST science, design, and technology needs presented to and discussed with SMD ASD on 27 June.

Next steps include

- Input on technology needs to Cosmic Origins and Exoplanet Exploration Program Offices, Offices of Chief Technologist and Scientist, and HQ STMD.
- Further develop technology roadmap and investment plan
- Open discussion on joint technology funding with industry and OGAs

carl.m.stahle@nasa.gov; 301-286-6182

Detailed ATLAST Technology Priorities:

Telescope Design Parameters

Notional Instrument Suite

Technology Priority Quad Charts

Technology Gap Analysis

Table 1: Telescope Design Parameters

Telescope Parameter	Consensus Requirement
Primary Mirror Aperture	≥ 8 meters
Primary Mirror Temperature	~20 C, pending detailed thermal design
UV Coverage	100 nm (90 nm goal) – 300 nm
Vis/NIR Coverage	300 nm – 2500 nm
Mid-IR Coverage	Under evaluation to ~ 8000 nm
Vis/NIR Image Quality	Diffraction-limited performance at 500 nm
Stray Light	Zodi-limited in 400 nm – 2000 nm wavelengths
Wavefront Error Stability for Exoplanet Imaging Using an Internal Coronagraph	1×10^{-10} system contrast < 10 pm rms residual system WFE for < 10 min bandpass between λ/D and $10\lambda/D$

Tale 2: Notional Science Instruments Design Parameters

Science Instrument Parameter	Consensus Requirement
UV Imager	100 nm (90 nm goal) – 300 nm FOV = 1 – 2 arcmin
UV Spectrograph	100 nm (90 nm goal) – 300 nm R = 20,000 – 300,000, multiple modes FOV = 1 – 2 arcmin Multi-object spectroscopy capability
Vis/NIR Imager	300 – 2500 nm FOV = 4 – 8 arcmin Nyquist sampled at 500 nm
Vis/NIR Spectrograph	300 – 2500 nm R = 100, 500, 2000 FOV = 3 – 4 arcmin
Starlight Suppression System	10^{-10} contrast (raw) 10^{-11} contrast stability over several days Inner working angle of ~ 40 mas
Exoplanet Imager	Near-UV and Visible channel FOV~ 10 arcsec
Exoplanet Spectrograph	300 – 2500 nm R = 70, 500 FOV ~ 1 arcsec

NB: Mid-IR instrument TBD pending performance assessment.

ATLAST Technology Priority: Starlight Suppression System

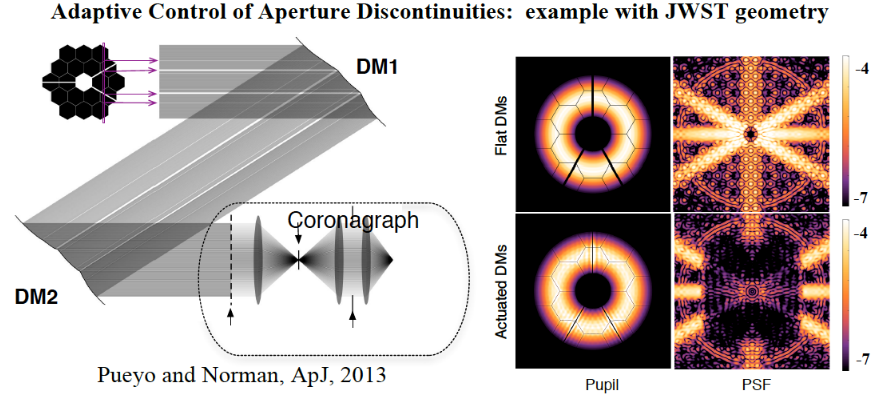
POCs: Stuart Shaklan, JPL, stuart.b.shaklan@jpl.nasa.gov
Matthew Bolcar, NASA GSFC, matthew.bolcar@nasa.gov

Description and Objectives:

- Develop starlight suppression system capable of 10^{-10} raw image contrast across the visible band
- Reduce impact to telescope wavefront thermal and dynamic stability requirements

Key Challenge/Innovation:

- 10^{-10} raw image contrast; 10^{-11} contrast stability
- Compatible with segmented aperture geometry
- 40 mas inner working angle (IWA)
- Broad, visible-band operation



Pueyo and Norman, ApJ, 2013

Approach:

- Parallel development to achieve requirements on contrast, IWA, and bandpass
- Develop both internal coronagraph and starshade
- Identify technologies that relax stability requirements on telescope
- Test coronagraphs on a vacuum segmented-aperture testbed

Potential Collaborators:

- NASA Centers (GSFC, JPL)
- STScI, universities, industry

Development Period:

- FY15-FY19

Key Milestones:

- Parallel starlight suppression tech. development
- Concept testing on vacuum segmented-aperture testbed
- Downselect to ATLAST candidate technologies
- Whitepaper for 2020 Decadal Survey

Other Applications:

- Complement development of smaller class missions, e.g. Probe-class and WFIRST-AFTA coronagraph

TRL_{in} = 2 - 4 ***TRL_{target} = 5***

ATLAST Technology Priority: Telescope Mechanical Isolation System

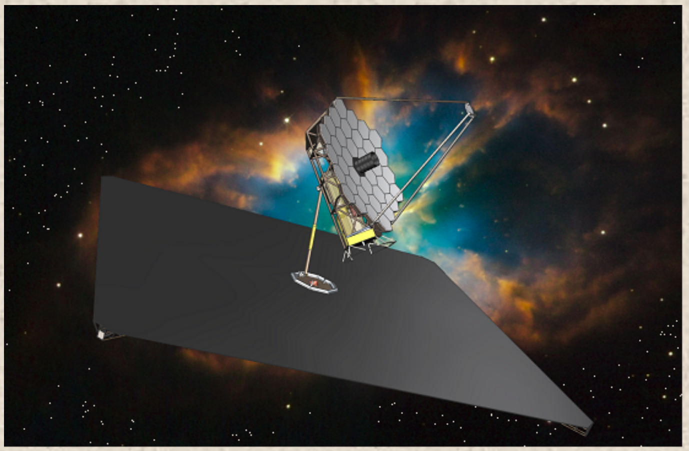
POC: Gary Mosier, NASA GSFC, gary.e.mosier@nasa.gov

Description and Objectives:

- Develop system-integrated vibration isolation technologies for telescope for starlight suppression system
- Establish capability to model and test vibration effects on segmented optics

Key Challenge/Innovation:

- Line of sight pointing stability of 0.1 to 1.0 mas
- System wavefront stability < 0.01 nm (TBR)
- Total system vibration isolation of 140 dB
- Vibration isolated mass of 5000 kg or more



Approach:

- Develop test facilities that are capable of testing vibration effects on optics, particularly on segmented optics
- Modeling/model validation to build Finite Element Model of the telescope under test

Potential Collaborators:

- NASA Centers (GSFC, JPL, MSFC)
- Industry
- Other Government Agencies

Development Period:

- FY15 – FY19

Key Milestones:

- Competitive call for isolation technologies
- Develop isolation testbed in air/ambient
- Develop isolation testbest in vacuum
- Test of isolation technologies on testbed

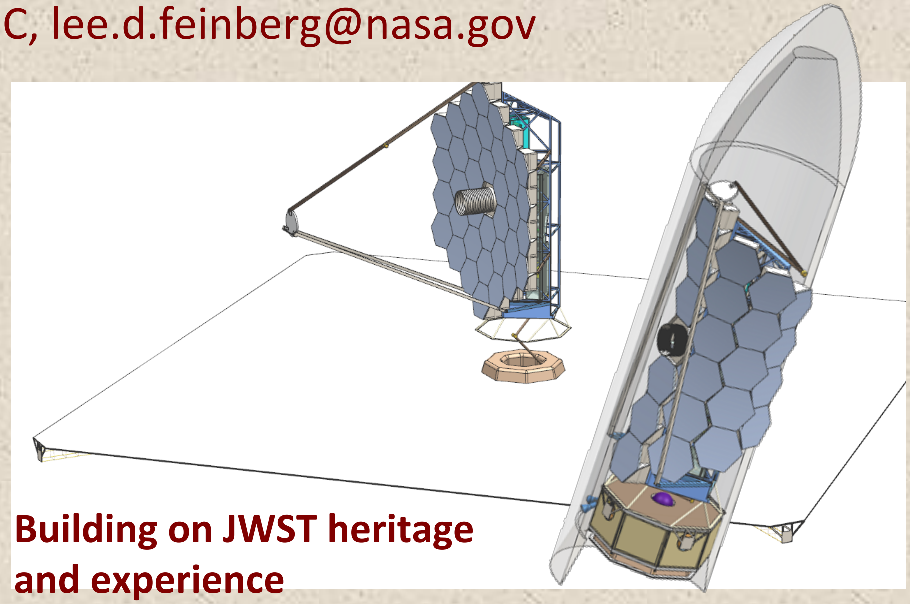
Other Applications:

- Cross-cutting for spaceflight missions where vibration isolation is critical, e.g. optical comm, instruments on ISS, interferometry

$TRL_{in} = 3 - 4$ $TRL_{target} = 5$

ATLAST Technology Priority:
Active Optical System – Optical System Design

POC: Lee Feinberg, NASA GSFC, lee.d.feinberg@nasa.gov



Building on JWST heritage and experience

Description and Objectives:

- Multidisciplinary design study for a 10-meter class space ***Optical Telescope***
- Establish feasibility, guide technology investment, and prepare for 2020 Decadal Survey

Key Challenge/Innovation:

- Diffraction-limited optical quality
- 10 pm wavefront sensing, metrology and control
- 10 pm wavefront stability over 10 min
- Low cost, low mass, and rapid fabrication

Approach:

- Lightweight glass or SiC primary mirrors
- Active thermal control for stability
- System-level vibration damping and isolation
- High-precision actuation

Potential Collaborators:

- NASA Centers (GSFC, JPL, MSFC)
- Institutions (STScI, universities, …)
- Mirror vendors
- System contractors

Development Period:

- FY15 – FY19

Key Milestones:

- Point design studies: segmented vs. monolithic apertures; active vs. passive optics; etc.
- Technology plan
- Conceptual design
- Design study for 2020 Decadal Survey

Other Applications:

- Study will inform development of other, smaller potential missions.

TRL_{in} = 2 - 4 ***TRL_{target} = 5***

ATLAST Technology Priority:
Active Optical System - Segmented Mirror System Development

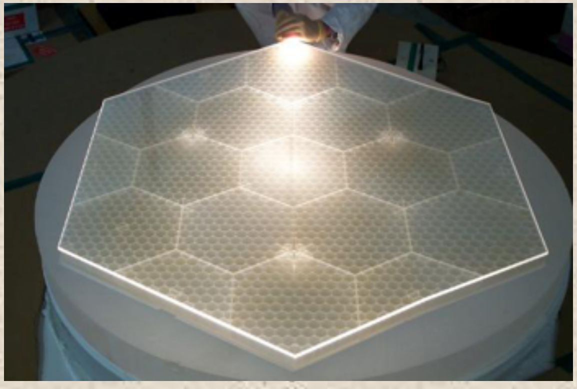
POC: Dave Redding, JPL, david.c.redding@jpl.nasa.gov

Description and Objectives:

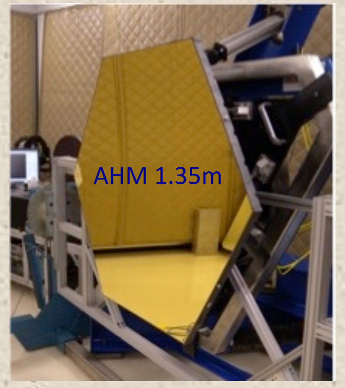
- Develop ***mirror systems*** for a 10-meter class space Optical Telescope
- Demonstrate TRL 5 through thermal-optical test
- Validate models for future system design

Key Challenge/Innovation:

- Diffraction-limited optical quality
- Wavefront stability to 10 pm per 10 min
- UV compatibility (μroughness, contamination, …)
- Low cost, low mass, and rapid fabrication



MMSD Lightweight ULE Segment Substrate



AHM SiC-based Segment Substrate

Approach:

- Utilize existing mirror segments developed by NASA and non-NASA sponsors
- Complete 2 or more as *mirror systems*, with thermal control, mounts, and actuators (if used)
- Model mirror system performance
- Test mirror performance at MSFC XRCF, to verify WF stability and validate models

Potential Collaborators:

- NASA Centers (JPL, MSFC, GSFC)
- Mirror vendors

Development Period:

- FY15 – FY19

Key Milestones:

- Competition to select participants
- Completion of mirror system designs
- Completion of mirror systems for test
- Completion of thermal-optical testing
- Completion of analysis and final repor

Other Applications:

- Mirror development will open useful options for smaller missions

TRL_{in} = 2 - 4 ***TRL_{target} = 5***

ATLAST Technology Priority: Detectors

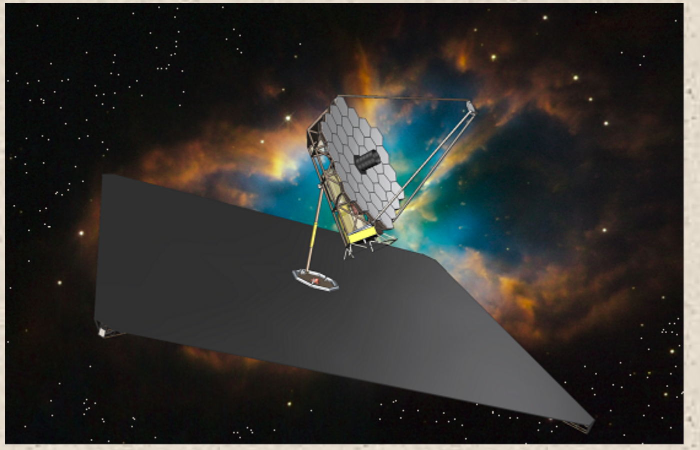
POC: Bernard Rauscher, NASA GSFC, bernard.j.rauscher@nasa.gov

Description and Objectives:

- Develop UV-Vis-NIR detector to enable ATLAST science
- Demonstrate by test that these meet ATLAST performance and environmental requirements

Key Challenge/Innovation:

- Meeting visible blindness, radiation, and QE in UV
- Providing deep full wells and low persistence in a radiation tolerant detector architecture (CCDs are not rad. hard)
- No detector technology currently meets read noise (<<1 e^-) and dark current < 0.004 e/s/pix requirements in NIR



Approach:

- Visible-blind, high QE (>50%), rad-tolerant arrays to enable UV imaging and spectroscopy
- Deep full wells with low persistence and radiation tolerance enable transit imaging and spectroscopy at all wavelengths
- Photon counting NIR arrays (read noise $\ll 1\ e^-$; dark current < 0.004 e^-/s/pix) enable coronagraphic spectroscopy for biosignature characterization and starlight suppression wavefront sensing

Potential Collaborators:

- Innovative partnerships of all kinds should be encouraged
- University/Industry/Government partnerships should be encouraged

Development Period:

- FY15 – FY19

Key Milestones:

- Demonstration of a visible blind, rad hard, high QE UV detector array
- Demonstration of a rad hard, visible wavelength detector having wells >2×10^5 e^- deep and other performance parameters at least as good as a modern astronomy CCD
- Demonstration of a near-IR optimized array that simultaneously detects individual photons and has a dark count rate < 0.004 e^-/s/pix

Other Applications:

- Broad applicability to almost any NASA science mission in the UV through NIR. Other applications include optical communications and national security remote sensing

$TRL_{in} = 3$ ***$TRL_{target} = 5$***

ATLAST Technology Priority: Mirror Coatings

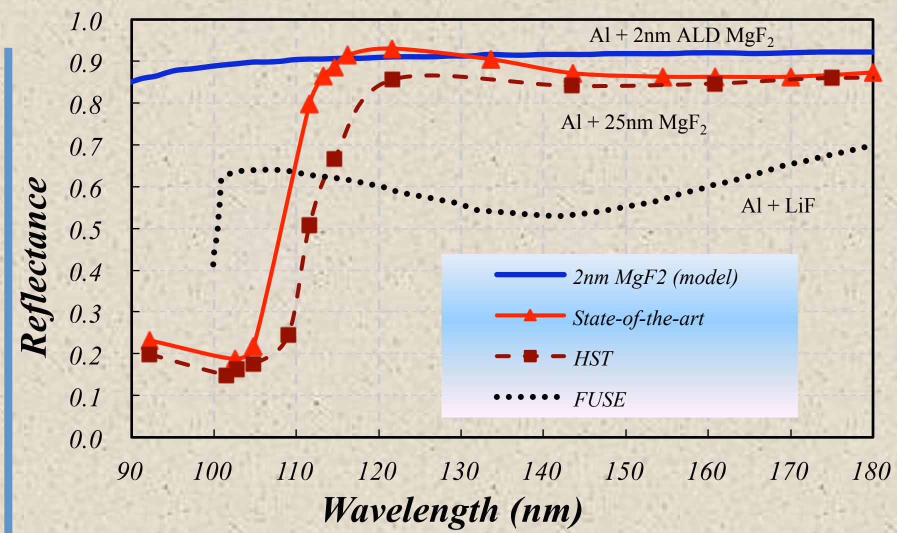
POCs: Manuel Quijada, GSFC, Manuel.a.Quijada@nasa.gov
Kunjithapatham Balasubramanian, JPL, kunjithapatham.balasubramanian@jpl.nasa.gov

Description and Objectives:

- Develop high-reflectivity coatings to support starlight suppression and high-throughput UV observations
- High uniformity (<1%); large spectral range (90 – 2500 nm); and low polarization (<1%; 400 - 1000 nm) for high contrast imaging

Key Challenge/Innovation:

- High reflectivity (> 90-95%) in the 90 to 2500 nm range
- Scaling up coatings to large diameter (meters) mirror substrates
- Maintain low polarization (< 1%) over wide spectral range



Approach:

- Develop conventional technologies such as physical vapor deposition with precision controls for producing high-performance mirror coatings on large diameter substrate
- Develop and mature new coating technologies such as atomic layer deposition (ALD)

Potential Collaborators :

- Industry partners through NASA SBIR program

Development Period:

- FY14 – FY19

Key Milestones:

- Achieving > 90 % reflectivity (100 to 2500nm) on test coupons with conventional and/or ALD coating processes
- Demonstration of a scaling up process by coating coupons over a large diameter substrate area

Other Applications

- Other optical components such as filters and beamsplitters required in complex optical systems

TRL_{in} = 3 ***TRL_{target} = 5***

Technology Gap Analysis

Driving Mission Parameter	Need	Comparison to State of the Art
Wavefront Error Stability	<10 pm over 10 min residual WFE over the λ/D to 10λ/D spatial frequency band	1000x < JWST (over days)
Contrast (planet/star)	10^{-10} (raw) 10^{-11} stability over several days	10x < WFIRST-AFTA
Aperture	≥ 8 meters	4x > HST; 1.2x > JWST
Detector Needs	***UV*** Quantum efficiency: > 50% Visible blind for imaging	3 – 6x HST
	Vis/NIR *Imaging Spectroscopy:* High QE, Large formats, Broad band, low dark/read noise for sky limited imaging, dark limited spectroscopy, radiation hard *Starlight Suppression:* Medium format; deep full well, extremely low latent images	Visible CCDs are not rad hard for use at Sun-Earth L2 NIR: JWST, WFIRST- AFTA
	Photon Counting Vis/NIR Transit imaging and spectroscopy, deep full well, low latent image, WFSC for coronagraph, very low dark count rate for spectrograph	Visible: Lab experiments NIR: No detector technology currently meets low read noise and dark current needs
UV Coverage	Good sensitivity to 90 nm Multi-object Spectroscopy	Shorter than HST Not done by HST

Table 4a: Starlight Suppression System

Technology	Sub Areas	Key Metrics	Need	State of the Art	TRL
Starlight Suppression System	Internal Coronagraph	Contrast (raw)	1×10^{-10}	5×10^{-10} (unobscured pupil) 1×10^{-8} (obscured pupil, monochromatic)	2 - 4
		IWA (λ/D)	2 - 3	4	
		Bandpass	Broad	2% – 20%	
	External Starshade	Contrast (raw)	1×10^{-10}	1×10^{-7}	
		IWA (λ/D)	2 - 3	Few	
		Bandpass	Broad	Broad	

Table 4b: Telescope Isolation System

Technology	Sub Areas	Key Metrics	Need	State of the Art	TRL
Telescope Isolation System	Reaction wheels	Attenuation > 40 Hz (dB)	140	80	3 – 4
	Active Isolation System				
	Passive Isolation System				

Table 4c: Active Optical System

Technology	Sub Areas	Key Metrics	Need	State of the Art	TRL
Optical System	Primary Mirror Assembly Wavefront Sensing and Control for Telescope	Aperture Diameter (m)	≥ 8	6.5 (JWST) 2.4 (HST)	2 - 6
		Areal Density (kg/m^2)	< 36 (EELV) < 500 (SLS)	70 (JWST) 460 (HST)	
		Areal Cost ($\$M/m^2$)	< 2	12 (JWST)	
		Surface Figure Error (nm rms)	< 7	< 7 (HST) 25 (JWST)	
		Mechanical WFE Stability (pm rms/10 min)	< 7	50 nm/14 days (JWST)	
		Thermal WFE Stability (pm rms/10 min)	< 7	50 nm/14 days (JWST)	
		Autonomous closed-loop onboard control (GFLOPS/W)*	> 100	< 20 (SpaceCube 1.0)	
		Control Bandwidth	1 per 5 min	1 per 14 days (JWST)	

*Giga-Floating Point Operations per Second per Watt

Table 4d: Detectors

Technology	Sub Areas	Key Metrics	Need	State of the Art	TRL
Detectors	UV (Visible Blind)	QE (%)	> 50	5 - 20	3 - 4
		Noise (elect rms)	< 5	< 5	
		Format (Mpixel)	4	1	
	Vis/NIR	QE (%)	> 80	> 80	
		Noise (elect rms)	< 5	< 5	
		Format (Mpixel)	16	16	
		Radiation Tolerance	Rad hard at L2	Visible CCDs not rad hard at L2	
	Photon Counting Vis/NIR	QE (%)	> 80	> 60 (Visible only)	
		Read Noise (elect rms) Dark Current (e/s/pixel)	< 1 <0.004	EMCCDs have been used to count photons in the visible. Reducing clock induced charge would be beneficial. HgCdTe arrays have been used to count photons at much higher dark count rates	
		Format (Mpixel)	4	1	

Table 4e: Mirror Coatings

Technology	Key Metrics	Need	State of the Art	TRL
Mirror Coatings	Wavelength (nm)	90 - 2500	90 - 2500	3
	Reflectivity (%)	> 90	< 50; 90 – 120 nm ~ 85; 120 – 300 nm > 90; 300 – 2500 nm	
	Uniformity (%)	< 1	2	
	Polarization (%)	< 1	1	