Astro2020 APC White Paper

Active Telescopes for Future Space Astronomy Missions

Relevant to High Contrast Systems, Ultra-stable Systems, Exoplanet Science, General Astrophysics, Solar System

Principal Author:

Name: Charles Lawrence

Institution: Jet Propulsion Laboratory, California Institute of Technology

Email: Charles.R.Lawrence@jpl.nasa.gov

Co-Authors:

David Redding, John Steeves, Todd Gaier, Randall Bartman, Claudia Pineda, Michael Werner, Kevin Hurd, Howard Tseng, Fai Mok, Oliver Lay, Alireza Azizi, Alex Ksendzov, T. Nicholas Gautier, Eric Cady, Jeff Jewell, J. Kent Wallace

Jet Propulsion Laboratory, California Institute of Technology

Michael Rodgers

Synopsis, Inc.

Jon Arenberg, Roman Hachkowsky, Michael P. Smith

Northrup Grumman Xinetics

Acknowledgements:

A part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Active Telescopes for Future Space Astronomy Missions

1 Background

Future space astronomy missions from ultraviolet to millimeter wavelengths require telescopes with capabilities beyond what has been achieved in the past. Size, wavefront error, temperature, risk, manufacturability, and cost are important factors, separately and in combination. LUVOIR calls for deployed apertures as large as 15 m in diameter, OST for operational temperatures as low as 4.5 K, LUVOIR and HabEx for exquisite optical quality[1-5]. Methods to construct large telescopes in space are also under development[6].

This paper introduces fully-active telescopes, with cryo-capable mirrors with hundreds or thousands of actuators, metrology systems, picometer-precision wavefront sensing and control techniques, and the electronics and software to drive them. We show how they operate in an integrated system, and how they meet the performance requirements of future missions. We show the important progress that has already been achieved. We request that Astro2020 recommend substantial technology development funding in the coming years to bring two key technologies – highly actuated cryo mirrors, and its associated metrology – to flight readiness.

Active telescopes sense and correct static and dynamic optical errors, providing these missions with in-situ wavefront correction capabilities in a variety of operating conditions. This reduces accuracy requirements on many parts of the system, and provides a level of assurance against unknown thermal distortions, gravity release effects, imperfect STOP models, long-term material creep, and dynamical disturbances. Active optics can also enable a telescope to operate in widely varying conditions, i.e., from room to cryogenic temperatures, and from 1g to 0g.

Simply put, this approach allows a telescope to be assembled and deployed only to mechanical tolerances, with the active optics providing on-orbit alignment and figure control to achieve UV tolerances. It allows for correction of

History – Arguably the first mission with an active telescope was Hubble, launched with a flawed primary mirror that threatened mission failure. The mirror errors were measured using star images – wavefront sensing – and ground data, and then corrected by astronauts replacing instruments with new ones with compensating optics.

The first operating active telescope for space astronomy will be JWST, whose primary mirror is formed from 18 moveable and (minimally) deformable segments. JWST will measure its post-launch, post-deployment, post-cooldown wavefront errors using star images and spectra, and then reposition and change the radius of curvature of its segments by command from the ground, to establish IR diffraction-limited performance across its wide field of view.

LUVOIR and HabEx use active optics to achieve diffraction-limited imaging at 400 nm wavelength, and wavefront stability in the picometers. LUVOIR has moveable ULE segments and edge sensors to continuously measure segment-to-segment alignments. HabEx has a low-order-deformable, 4-m monolithic Zerodur primary. Both have image-based wavefront sensing, and laser metrology for continuous telescope alignment. Both use small deformable mirrors with low- and high-order wavefront sensing and control in their coronagraphs, for high contrast imaging over small fields of view.

HabEx and LUVOIR would be operated near room temperature, the sweet spot for their low-expansion glass mirrors, avoiding the historical complications of making and testing cold optics and structures and controlling contamination for the UV band. Their long-wavelength coverage is therefore limited, to 1.8 μm (HabEx), 2 um (LUVOIR coronagraph), and 2.5 um (LUVOIR HDI), which precludes a wide range of compelling astronomical and exoplanet science.

This white paper introduces an alternative approach that uses active optics to assure performance with reduced risk. The primary thrust here is to achieve a broader spectral capability for the next NASA space telescope, covering UV to Mid IR spectral bands, for exoplanet science and astronomy in general. This approach could be competitive for a LUVOIR, HabEx or even OST-type mission, but not without additional investment. The fully-active, cryo-capable mirrors described here build on demonstrated active mirrors and control systems developed through JPL-led NASA and non-NASA technology projects. While active system aspects are being incorporated in telescopes being built and designed today, a fully-active system cannot yet be prescribed for a mission. But the potential for increased capability with reduced risk and cost is there. We believe that flight-readiness can be achieved in about 5 years, for a cost of about $50 M. We ask Astro2020 to recommend such a development program.

2 Key Science Goals and Objectives

The UVOIR science programs outlined in the HabEx and LUVOIR reports provide truly breakthrough scientific opportunities, for exoplanet discovery and characterization, for tracing galaxy evolution, for star and planetary system formation studies, and for study of our own solar system. But as mentioned previously, their wavelength coverage is limited to <2.5 μm, not for scientific reasons, but because the thermal emission background from their room-temperature telescopes overwhelms the astronomical background at longer wavelengths. The same is true for Hubble. Because the approach to active telescopes that we describe here will work from room temperature to cryo temperatures, that non-scientific wavelength limitation can be lifted.

What is gained by extending the capabilities of a large space telescope to encompass longer wavelengths? The scientific case has been made overwhelmingly, in the arguments for Spitzer, JWST, and in many other white papers submitted to Astro2020. We have neither space nor need to repeat those arguments here; our subject is further development of technology that can enable telescopes to cover from UV to mid-IR wavelengths, and also from mid-IR to far-IR wavelengths. So we will simply list some of the science enabled, to reinforce the advantages of the active approach that we are describing.

For exoplanet atmospheric characterization, Werner et al.[7] and Swain et al.[8] show that spectroscopic observations in the 2.5–5 μm band access strong spectral lines of four key molecular species – H_2O, CO, CO_2, and CH_4 – that could prove essential for verifying life-driven atmospheric chemistries. Important species like O_3, SO_2, and NH_3 can also be studied at these wavelengths. The white papers emphasize what can be done with transit spectroscopy and a cold telescope. More yet can be done on a cold telescope using direct imaging methods.

For astrophysics generally, thermal emission from objects whose physical temperature lies in the 500-3000 K range peaks in the 1–5 μm band. In our galaxy, this includes low-mass main sequence stars and brown dwarfs; Brackett lines in H; rotational-vibrational and rotational lines of H_2; the shortest PAH feature; vibrational bands of H_2O, CO_2, CO, and CH_4; Hα at higher redshifts; and the surfaces of many Solar System bodies. Starlight from galaxies during the peak of star formation at z~2 and out to z>10 will be redshifted into this band. Of particular importance, as discussed below, will be studies of exoplanets.

Sky surveys have been made by WISE from 3-to-5 μm; however, covering large sky areas with much greater angular resolution and sensitivity remains a high priority. One of the important advantages of activating the primary mirror is that it corrects wavefront errors over the entire field of view. Deformable secondaries and other downstream mirrors can correct only over smaller and smaller fields of view, and might suffice for exoplanet studies, but many astrophysics topics require large fields of view (as shown by WFIRST).

3 Technical Overview

3.1 Active Telescope Architecture

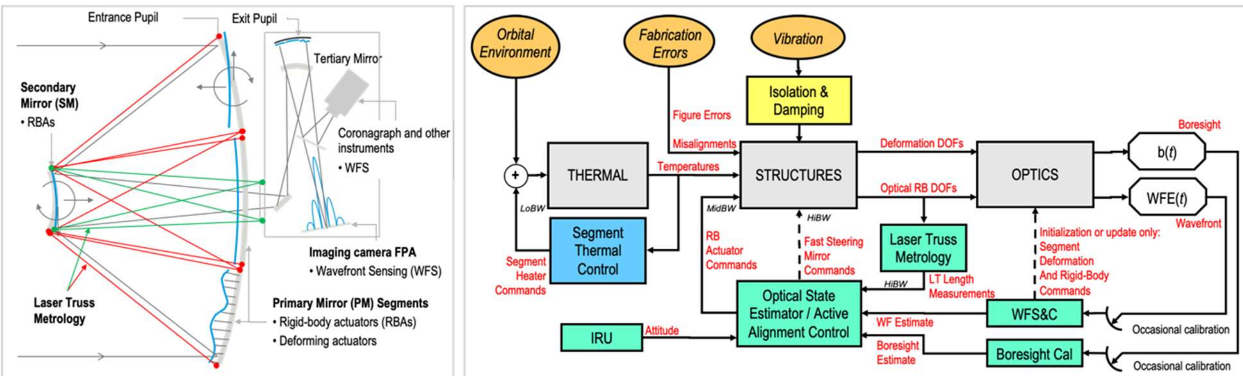


Figure 1. (left) *Schematic showing elements of active optics: moveable SM; moveable and deformable PM segments; imaging camera used for image-based WF sensing; plus laser truss metrology.* (right) *Block diagram showing signal flow in the active optics control system: WF sensing and control measures overall WF errors, and sets the control set points for the laser metrology system; and the laser truss metrology keeps the telescope alignments in place.*

Active Telescope for Space Astronomy (ATSA): An active telescope is more complex than a simple static telescope, as Wavefront Sensing and Control (WFSC) operations are needed to phase the mirrors after launch, and Metrology (MET) is used to maintain optical alignment thereafter. However, WFSC and MET provide resilience to problems that have limited other missions in the past: optical testing errors; unexpected environmental conditions; gravity release prediction errors; changes induced by launch loads; misalignments between instruments; and mirror fabrication errors. All these can be corrected on orbit by the active telescope system, reducing mission performance risk, and relaxing fabrication and alignment tolerances.

The level of actuation in the system is dependent on the mission requirements. Segmented ground-based telescopes (Keck, TMT), include rigid-body actuators (RBAs) on their segments to phase the primary mirror, and warping harnesses to adjust their figure. JWST includes RBAs but also implements a radius of curvature actuator on each segment for an additional level of control. Here we extend this concept by incorporating tens to hundreds of surface figure actuators (SFAs) on each segment, enabling the correction of higher-order errors. Since the segment SFAs correct for optical aberrations at the source (i.e., on the PM itself), the correction is valid over the entire field of view of the telescope.

3.2 Active Mirrors

JPL, in partnership with AOA Xinetics, has developed active mirrors for room-temperature UVOIR applications. Figure 2 shows a typical mirror, with surface-parallel actuators embedded into the ribs of its cast isogrid back structure. The actuators are electroactive ceramics, electrostrictive (PMN-PT) for warm mirrors or piezoelectric (PZT) for cold applications and are installed in a half-extended condition, giving them the ability to both pull and push on the mirror. Typical surface figure shape change due to individual actuators, as well as the beginning and end state figure, are shown in Fig. 3.

Figure 2. Three views of a SiC mirror for warm VIS applications, showing the as-cast part with its isogrid back structure, ceramic actuators integrated into the isogrid main ribs, and the facesheet.

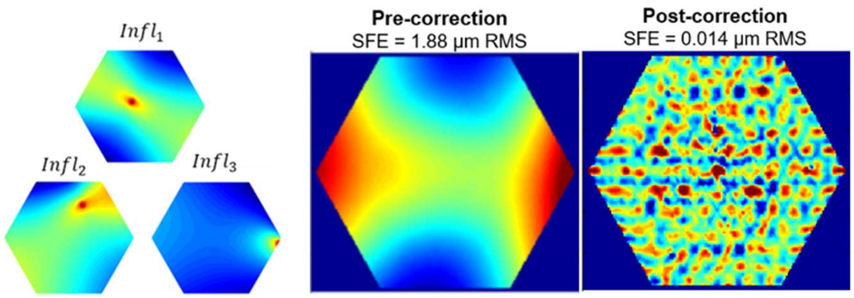


Figure 3. (left) Three measured actuator influence functions, showing the characteristic localized bump and global shape change characteristic of active SiC mirrors. (center and right) Before and after correction data from a 1.35 m AHM SiC mirror, showing 14 nm RMS surface error after correction.

Building off the work performed for room-temperature applications, a 15 cm Cryo Active Mirror (CAM) was built to extend the active SiC technology for use at cryogenic temperatures[9] (Fig. 4). The CAM contained 12 cryo-compatible actuators attached to the SiC substrate using custom tabs. Tab material and shape were chosen to generate a net negative CTE to compensate actuator/SiC CTE differences, to athermalize the complete mirror-tab-actuator structures at room temperature and at the target 30K temperature. The CAM mirror was tested at a full range of temperatures, from 290 K to 26 K, successfully demonstrating the functionality of the cryogenic actuators and the athermalization scheme.

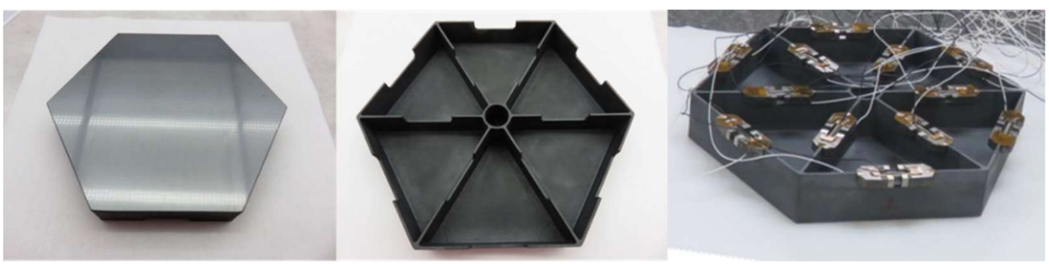


Figure 4. Subscale (0.15 m diameter) Cryo Active Mirror (CAM) built and tested in FY16. The re-entrant tab design was used to match actuator and SiC substrate deformation at room temperature and at 30K, to preserve mirror figure without requiring actuator stroke at those two temperatures.

Why Use SiC for Active Mirrors? Ultra-Low Expansion (ULE) glass mirrors have long been preferred for space optics because ULE has a near-zero Coefficient of Thermal Expansion (CTE). However, this is true only at room temperature. At 100K, SiC has a lower absolute CTE than ULE. Moreover, it has 100 times better thermal diffusivity, eight times higher specific strength, four times higher specific stiffness, and 10 times higher design stress. These are major advantages in building mirrors that are stiff, light, and fast to reach thermal equilibrium. We are familiar with these advantages because, working with AOA Xinetics, we have built and tested many active SiC mirrors, including space qualification testing of a prototype 1.35 m hexagonal segment subsystem, with integrated FCAs, mounts and thermal controls[11, 12].

Previous efforts with active SiC mirrors implemented "nanolaminate" facesheets, sputter deposited metal foils that are transfer-bonded onto SiC substrates, to achieve the reflective front surface of the mirror.[11] However, for mirrors operating at 100 K, the membrane stress imparted by the nanolaminates are too large and thus more traditional polishing techniques are required. A direct polish of the Xinetics Ceraform™ SiC can achieve about 10 Å RMS microroughness and is limited by the bimodal nature of the material (SiC matrix fully densified with Si). For UV mirrors, the SiC surface can be clad with amorphous Si or CVD SiC before polishing, to achieve 2-Å surface quality after polishing.[13, 14] The cladding process is now widely used in industry on a scale up to 60 cm, for room temperature; it remains to demonstrate UV quality surface and figure on a completed lightweight SiC mirror larger than 1 meter, and over a wide temperature range.

3.3 Metrology

To ensure that the telescope remains precisely in the optimal configuration determined by WFSC, in-space laser metrology (MET) will continuously measure the position of each major optical assembly, using the RBAs in closed-loop control to keep the telescope aligned (Fig. 1). In this technique, a set of laser distance gauges are attached to the primary mirror segments and directed to corner cube reflectors next to the secondary mirror. A second set of gauges are mounted on or near the optical bench of the telescope, also directed towards the secondary mirror. The gauges measure small changes in the rigid body pose of each optic relative to the optical bench. These feed into a control loop that corrects for the misalignments using the segment and SM RBAs, to maintain system-level alignment of the telescope during observations.

In-space laser metrology has been under active development since the late 1990s. The Space Interferometry Mission (SIM) project demonstrated picometer precision measurements using large and heavy components in the lab. LISA Pathfinder and Grace Follow-On have flown picometer-capable phasemeter electronics. For space telescopes, JPL has developed, built, and tested lightweight, compact laser distance gauges (LDGs), and designed laser truss networks to continuously measure the alignment state of the major optical assemblies to nanometer-level accuracy (Figure 5)[15]. Lockheed Martin also has developed picometer LDGs for telescopes[16].

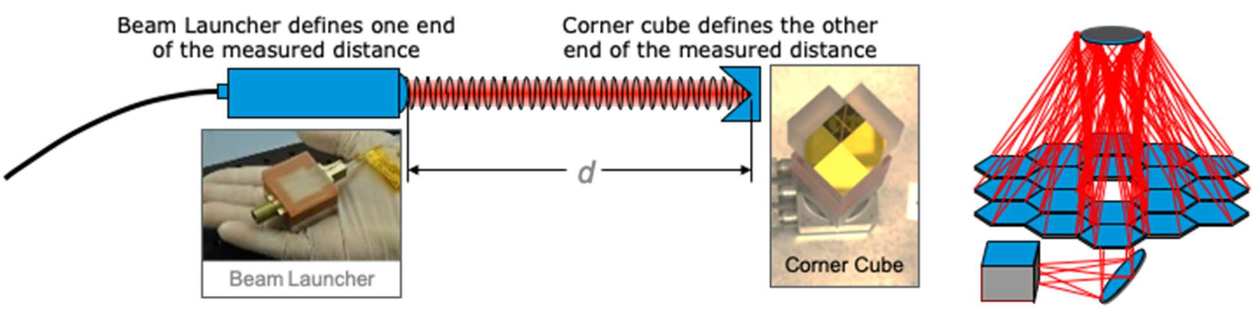


Figure 5. (left) *A laser distance gauge (LDG) provides accurate measurements of displacements between the beam launcher attached to one body, and the corner cube attached to another body.* (right) *An optical truss uses six LDGs between each segment and the SM, and six more from the optical bench to the SM to accurately measure 6DOF motions of each optic, for closed-loop alignment control.*

3.4 Wavefront Sensing and Control

Several wavefront sensing techniques exist to first establish (i.e., during commissioning) and then maintain telescope optical quality while in orbit. Most notably, image-based techniques estimate the wavefront error across the fields of view of each camera using star images and spectra from the science instruments processed on the ground. The primary mirror RBAs and FCAs, and the secondary mirror RBAs, use this information to optimize the system-level optical quality across all the instruments using essentially the same methods as JWST[18,19,20]. Occasional recalibration observations will monitor and correct long-term WF drifts.

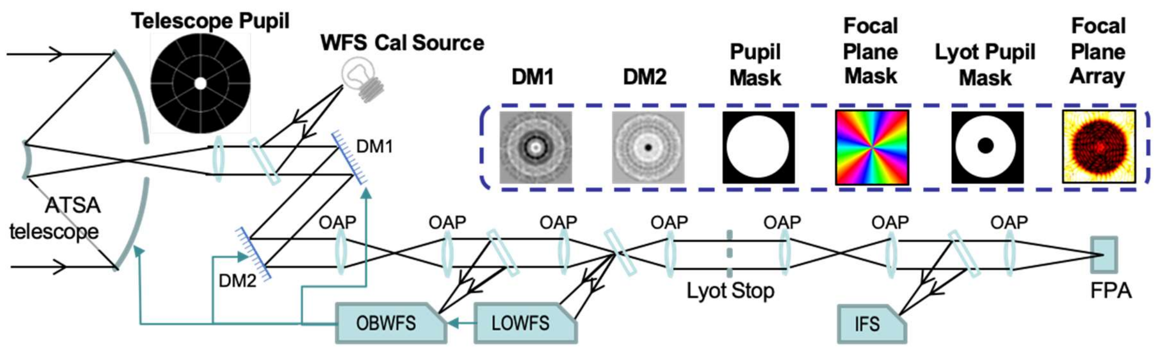


Figure 6. A Vector Vortex Coronagraph for the ATSA telescope. The two DMs are used to dig the dark hole discovery region, potentially with help from the active PM. Then low-order WF sensing (LOWFS) and high-order out-of-band WF sensing (OBWFS) operate during coronagraph observations to preserve the high-contrast WF. Changes in the measured WF are fed back to DM1, DM2, and the telescope active PM. An internal WFS calibration source provides for high-SNR OBWFS measurements for high spatial frequency corrections of DM and instrument drifts, and provides a DM servo mode.

However, the desire to detect and characterize Earth-like exoplanets via coronagraphic imaging imposes a new class of requirements on WFSC technology. In particular, wavefront stability on the order of tens of picometers is required for segmented aperture coronagraphic telescopes – a 1000x factor increase from non-coronagraphic UVOIR missions. Therefore, dedicated coronagraphic wavefront sensors are required in addition to those used to commission the telescope (Figure 6). WFIRST's Low-Order Wavefront Sensor (LOWFS), has demonstrated (via the High Contrast Imaging Testbed, HCIT) sensitivity at the picometer level, with photon fluxes representative of flight operation[21]. However, as the name suggests, the LOWFS is only able to detect changes of low spatial frequency. Telescopes implementing segmented apertures along with high-actuator count deformable mirrors, are susceptible to mid/high-spatial frequency errors and therefore a sensor capable of detecting these changes is required. JPL has developed a high-order wavefront sensing testbed that extends the spatial bandpass of the LOWFS. The testbed is based on the Zernike Wavefront Sensor (ZWFS) concept, which implements the phase contrast technique[22]. This technique provides a simple, photon-efficient method of measuring changes in wavefront errors by modulating optical phase variations to intensity variations on a pupil-viewing camera. The testbed has demonstrated the ability to detect high-spatial frequency wavefront changes (i.e., due to deformable mirror actuator pokes) on the order of 200 picometers in an in-air laboratory setting.

4 Technology Drivers

Technology needs for a cold ATSA mission include six ATSA-specific items, plus 17 other items that are already identified in the LUVOIR or HabEx final reports, as shown in Table 1. In this paper we have addressed the top two telescope-specific ATSA-unique technologies, namely the Si-clad SiC mirrors and the cold MET. Of the remaining ATSA-specific technologies, cryo UV contamination is likely an engineering issue; cold DMs will benefit from active SiC mirror development; cold Micro Shutter Arrays derive from JWST hardware; and low-noise MIR detectors are under development.

Table 1. Technology needs for a cold ATSA mission, cross-referencing HabEx and LUVOIR. Related-to subsystems are Telescope (T), Starshade (SS), Spacecraft (SC), Coronagraph (C), and Instruments (I).

Technology	Needed by A/L/H (ATSA/LUVOIR/ HabEx)	Related to T/C/I/SC/SS
Si-clad SiC active mirrors	A	T
Cold MET	A	T
Cryp UV contamination	A	T
Cold DMs	A	C
Cold MSAs	A	I
Low-noise MIR detectors	A	I
RBAs	L, A	T
FUV coating	H, L, A	T, I
Microthrusters	H, L, A	SC
Starshade petal position	H, A	SS
Starshade petal shape	H, A	SS
Starshade edges	H, A	SS

Technology	Needed by A/L/H (ATSA/LUVOIR/ HabEx)	Related to T/C/I/SC/SS
Starshade modeling and V&V	H, A	SS
Starshade formation sensing	H, A	SS
Coronagraph architecture	H, L, A	C
LOWFS	H, L, A	C
OBWFS	L, A	C
DD UV+VIS EMCCDs	H, L, A	I
Deep Depletion VIS EMCCDs	H, L, A	I
APDs	H, A	I
UV MCP detectors	H, L, A	I
DD UV EMCCDs	H, L, A	I
MSAs	H, L, A	I

Summary: 6 ATSA-unique telescope technologies, 3 are telescope-related. 23 tech needs overall, 17 overlap HabEx and/or LUVOIR.

4.1 Next Steps

SiC active mirrors plan forward. JPL is funding risk reduction activities at AOA-Xinetics to further manufacturing-centric design activities that allow for uniform optical performance from deep cryogenic to room temperatures, including building small test pieces. Next steps, starting in 2020, would be to fabricate and test a complete full scale demonstrator mirror, to achieve TRL 5.

MET plan forward. The challenge for ATSA is twofold: to demonstrate sub 100 picometer LDG accuracies at 10 Hz BW; and to do it with hardware that can operate over the full range from room to cryogenic temperatures. The need for temperature resilience suggests that the JPL range-gated beam launcher design is to be preferred over the JPL and LM Planar Lightwave Circuit designs, as no complex parts need be cold. We recommend investment in development of temperature resilient fibers, connectors, adhesives, and test equipment; plus adoption of LISA phasemeter electronics, improved laser stability, and beam launcher temperature control for picometer performance. Successful demonstration of a flight-traceable LDG will establish TRL5 for ATSA MET.

WFSC plan forward. JPL is currently investigating methods to increase both the sensitivity and dynamic range of the ZWFS for implementation as the out-of-band WFS for high-contrast coronagraphs. In particular, the ZWFS testbed will be implemented in a more stable environment (isolated vacuum chamber), and the system performance will be demonstrated under in representative conditions (i.e., expected photon fluxes). This will establish TRL 5 for the ATSA.

Control electronics and cabling plan forward. The electronics will be built around intrinsically rad-hard ASICs, with ribbon cables. Thermal design is central.

System-level demonstration. Upon development of the key technology subsystems, it is intended to demonstrate system level performance using an active telescope testbed. This testbed will be operated in the stressing environments (i.e., 100K temperatures) with performance requirements traceable to the ATSA reference mission. This will establish TRL 6 for future active telescopes operating from UV to Mid-IR wavelengths.

System engineering study. The design, fabrication, integration, and testing of an active telescope require significant study. The requirements on component testing and system-level testing will be different than for non-active telescopes, particularly because cryogenic operating temperatures will be the norm. Cost is a major item of study, and ultimately what matters is the cost of the entire system, including integration and testing.

5 Organization, Partnerships, and Current Status

JPL has partnered with Northrop Grumman Xinetics for over two decades developing active silicon carbide optics, including repeated demonstration of UVOIR performance for room-temperature applications. Current activities focus on extending this technology to a broader range of operational temperatures. JPL/Xinetics are conducting "risk reduction" activities to ensure that future designs are robust and reliable from a manufacturing standpoint, including. characterization of fundamental material properties of the major mirror components over the full range of envisioned temperatures (293 to 40K). With this knowledge, reliable, robust, active mirror designs can be constructed.

Other JPL activities are synergistic with this effort. WFIRST CGI, and the High-Contrast Imaging Testbed (HCIT) are the current leaders in space-based coronagraphy, with several demonstrations related to active control and precision wavefront sensing. They are also investigating flight-compatible drive electronics, a key component to active telescope systems. Keck/TMT, are demonstrating what can be done on the ground for segmented aperture telescopes. Finally, laser metrology has been demonstrated in space with recent missions such as Grace Follow-on and LISA.

6 Schedule and Cost Estimates

A 4 year technology development plan is under development, working towards a multi-segment testbed containing full-scale active mirrors, laser metrology, WFSC, and low-power proximal electronics. The testbed will demonstrate system-level performance in environments traceable to the ATSA reference mission outlined in Appendix A. A phased development approach is adopted with key steps performed early on to buy down technical risk, including, subscale demonstrations and functional testbeds. Integrated optical/mechanical/ thermal models are under development for correlation to test results, and to make predictions on future designs. The current plan extends over 4 years and is estimated at approximately $50M to complete.

7 Summary

Building on a foundation developed under DOD funding, plus ongoing work on active components in nearly every telescope now under construction, we believe that a 5-year, $50 M program can bring active telescope systems to flight readiness for astronomy missions in space. The potential benefits of such systems in terms of science, reduced risk and cost, and scalabilty are substantial. A recommendation from Astro2020 that such a program be funded by NASA would hasten that future.

Appendix: ATSA Reference Mission, A Non-Deployed 6-Meter Active Telescope

We have begun a reference mission design study for a fully active, UV-to-MIR Active Telescope for Space Astronomy (ATSA) space telescope, to provide context for flowing science goals into subsystem technology requirements. The study addresses science goals from HabEx and LUVOIR, but pushes beyond their 1.8-2.5 μm limits to 5 μm wavelengths. This broader spectral range accesses more diagnostics for planetary atmospheres, helping rule out false positives for exoEarth discovery; and opens the full range of UV to MIR astronomy.

Aperture is at a premium for direct imaging of exoplanets, especially for longer wavelengths, but we sought to avoid the risk and complexities of a deployed telescope. We picked 6 meters for the ATSA aperture size, and developed a non-deployed, on-axis, segmented space telescope design that can be launched to L2 using an SLS-1B, with its 8.4 m short shroud. Figure 7 shows a CAD drawing of the telescope, its optical instruments, and a cylindrical spacecraft bus, in the payload shroud. It has a cylindrical outer barrel sunshield with a closeable cover that, when open, forms a scarf that shades the telescope for pointing directions from anti-sun to within 40° of the sun. ATSA optics would operate at 100K, thermally controlled above the orbital ambient temperature, for background-limited observations out to 5 um wavelength.

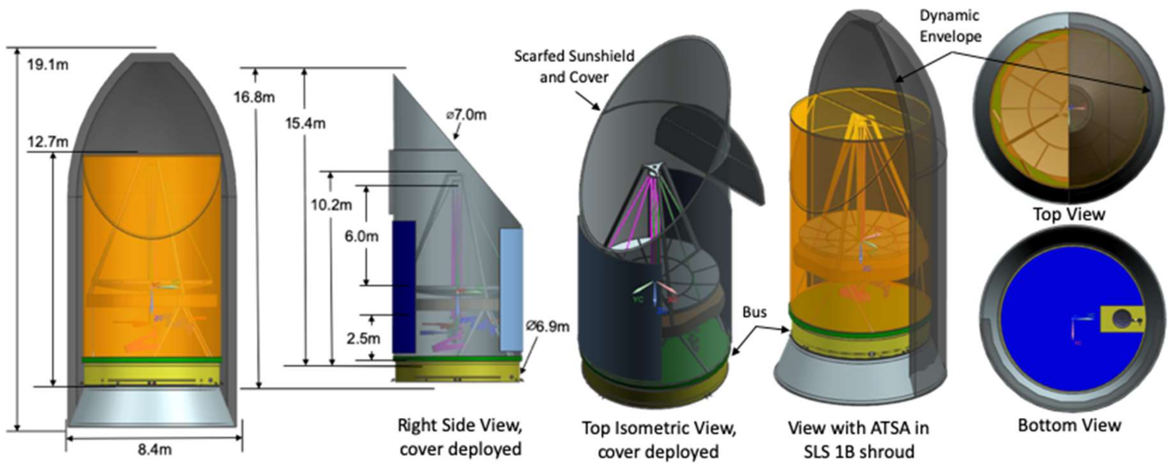
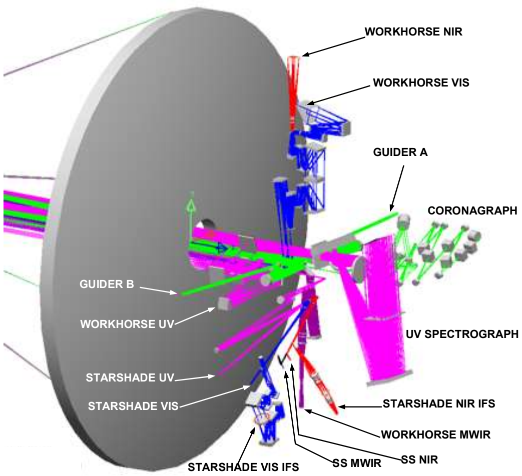


Figure 7. An Active Telescope for Space Astronomy (ATSA) design concept, shown in its operational, cover-open configuration, and as stowed in the SLS 1B launch vehicle.

We assessed whether a 6-m ATSA could provide a full UV-to-MIR instrument suite. This was done by scaling up the "HabEx3.2S" starshade-only alternative architecture design that is described in the HabEx final report[23]. The result was a full suite of instruments inspired by HabEx: a UV spectrograph with resolution to R=60,000; a Workhorse camera for UV, VIS, NIR, and MIR imaging and spectrometry; and a starshade camera, with UV, VIS, NIR and MIR channels, for guiding and high dynamic range imaging with a separately flown starshade (Fig. 8). We also added a simple IR coronagraph based on the WFIRST CGI design. The optical design for the telescope and its HabEx-derived instruments meet representative requirements for optical quality, field of view, and spectral and spatial resolution[4].

ATSA would be flown together with 72-meter wide starshade (Fig. 9), designed to provide a wide bandwidth, tight Inner Working Angle (IWA), and 10^{-10} contrast for a 6-meter telescope[24]. The IWA for each of the listed observational bands corresponds to about 1.7λ/D at the longest wavelength, λ. Starshade operations require maneuvering between each target, then stationkeeping during observations. More maneuvers along the line of sight would set up the different distances used to access different observational bands. It is expected that 50 to 100 targeting maneuvers would be possible, many more if the starshade is refueled on orbit.



#	Channel	WL (nm)	FOV	Pixel	F/#	Filters	Other mechanisms
1	UVS	115-300	3x3 amin	15 µm	< 65	7	Insertable MSA, F/16 Filter slider
2	WC UV	320-450	3x3 amin	12 µm	41	14	None
3	WC Vis	450-950	3x3 amin	12 µm	41	60	Insertable MSA at shared F/33 focus
4	WC NIR	950-1800	3x3 amin	10 µm	20	21	
5	WC MWIR	3000-5000	3x3 amin	TBD	10 assumed	TBD	TBD
6	SSC UV Imager	200-450	7 asec	13 µm	80	None	Pupil imaging lens. R=5 prism
7	SSC Vis Imager	450-1000	7.9 asec	12 µm	71	None	None
8	SSC Vis IFS	450-1000	1.25x1.25 asec	12 µm	1333 lenslet 6 FPA	None	Switch mirror
9	SSC NIR Imager	975-1800	7.9 asec	12 µm	51	None	Pupil imaging lens
10	SSC NIR IFS	975-1800	2.55x2.55 asec	12 µm	469 lenslet 3.36 FPA	None	Switch mirror
11	SSC MWIR	3000-5000	7.9 asec	12 µm	15 assumed	None	None
12	Coronagraph	MWIR	2.2 asec	TBD	WFIRST F/#	TBD	Several
13	Guider A	500-900	3.1 amin TFOR	13 µm	48	None	Scan mirror
14	Guider B	500-900	.285x.285 amin FPFOV	13 µm	48	None	Scan mirror

Figure 8. ATSA optical instruments include a UV Spectrograph (UVS), a general-purpose workhorse camera (WC) with UV, VIS, NIR and MIR imaging and spectrometry modes, a starshade camera (SSC) with UV, VIS and IR imaging, spectrometry and starshade guiding modes, and a coronagraph.

Starshade observations at MIR wavelengths would be limited by starshade thermal emissions, depending on starshade thermal design and on sun angle. Preliminary analysis based on current designs suggests that, if equipped with multiple layers of insulation, telescope-side temperatures could range from 120K when nearly edge-on to the sun, for observations to 4.9 μm wavelength, to 200K at the 40° closest pointing angle, allowing observations to about 2.3 μm wavelength.

RM12 Starshade for ATSA 6-meter Telescope Diameter = 72 meters, Petal length = 16 meters Minimum Fresnel number = 10			
Bandpass	150-500 nm	750-2500 nm	1.5-5 um
IWA to tips	31 mas	155 mas	310 mas
Distance	239,533 km	47,907 km	23,953 km

Figure 9. RM12 starshade provides high contrast ($<10^{-10}$), broadband imaging to a tight Inner Working Angle (IWA). For comparison, maximum Earth-Sun separation is 100 mas as seen from 10 parsec away. The IWA for the listed bands corresponds to about 1.7λ/D at the longest wavelength λ.

An ATSA coronagraph would provide a more agile direct-imaging option, making it possible to discover more planets, and to determine more planetary orbits. Coronagraph architecture could use LUVOIR A designs, as accommodating a segmented, obscured aperture[1]. An IR coronagraph could extend the exoplanet direct imaging capabilities of an ATSA into the MIR, beyond any limits imposed by the emission of a warm starshade, but at wider IWA. It would be simpler to implement than a VIS coronagraph, with relaxed telescope stability requirements.

Our study will continue, addressing the thermal system design: the scarfed sunshield; the 100K optics; cooling of electronics, detectors and back-end structures. We will investigate UV contamination issues for a 100K telescope, noting that the fully-enclosed barrel provides a controllable contamination environment, and that heaters on the optics will be able to evaporate much that condenses on them. We will continue to look at starshade and coronagraph performance, especially in the 2-5 μm band. The result will be a better understanding of the requirements for the fully active optics technologies.

References

1. LUVOIR Team. "The LUVOIR mission concept study interim report." *arXiv preprint arXiv:1809.09668* (2018).
2. Roberge, Aki, et al. "The Large UV / Optical / Infrared Surveyor (LUVOIR): Telling the Story of Life in the Universe". Astro 2020 APC Whitepaper (2019).
3. OST mission concept study team. "The Origins Space Telescope (OST) Mission Concept Study Interim Report." *arXiv preprint arXiv:1809.09702* (2018).
4. Gaudi, B. Scott, et al. "The habitable exoplanet observatory (HabEx) mission concept study interim report." *arXiv preprint arXiv:1809.09674* (2018).
5. HabEx White Paper
6. Siegler, Nicholas, Rudranarayan Mukherjee, and Harley Thronson. "Building the Future: The NASA in-Space Assembled Telescope Study." *American Astronomical Society Meeting Abstracts# 233*. Vol. 233. 2019.
7. Werner, Michael W., et al. "Extension of ATLAST/LUVOIR's capabilities to 5 μm or beyond." *Journal of Astronomical Telescopes, Instruments, and Systems* 2.4 (2016): 041205.
8. Swain, Mark, et al. "Maintaining Infrared Exoplanet Transit and Eclipse Measurement Capability In the Post JWST Era" Astro 2020 APC Whitepaper (2019).
9. D. Redding, E. Cady, K. Coste, J. Nissen, O. Polanco, C. Pineda, K. Hurd, H. Tseng, J. Quezada, S. Martin, J. Nissen, K. Schulz, J. Tesch, E. Cady, M. Rodgers, M. East, J. Mooney, C. Stark, "HabEx3.2S: a starshade-only habitable exoplanet imager alternative", Proc. SPIE 10698, Space Telescopes and Instrumentation 2018: Optical, Infrared, and Millimeter Wave, (2018).
10. Steeves, John, et al. "Active mirrors for future space telescopes." Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation III. Vol. 10706. International Society for Optics and Photonics, 2018.
11. Hickey, Gregory, et al. "Actuated hybrid mirrors for space telescopes." *Space Telescopes and Instrumentation 2010: Optical, Infrared, and Millimeter Wave*. Vol. 7731. International Society for Optics and Photonics, 2010.
12. D. Redding, "Advances in Telescope Technology: Mirror Alternatives for the Far IR", https://conference.ipac.caltech.edu/firsurveyor/system/media_files/binaries/44/original/26-FIR_Mirrors_V2.pdf?1433554389 (2015).
13. https://www.northropgrumman.com/BusinessVentures/AOAXinetics/AdvancedSystems/Documents/CERAFORM_SiC_DataSheet.pdf
14. Sheikh, David A. "Low-stress silicon cladding made by pulsed-ion-assisted evaporation." Material Technologies and Applications to Optics, Structures, Components, and Sub-Systems II. Vol. 9574. International Society for Optics and Photonics, 2015.
15. O. P. Lay, S. Dubovitsky, D. A. Shaddock, and B. Ware, "Coherent range-gated laser displacement metrology with compact optical head," Optics Letters, V32, N20, https://www.osapublishing.org/ol/abstract.cfm?uri=ol-32-20-2933 (2007).
16. Bell Jr, Raymond Mark, et al. "Robust heterodyne interferometer optical gauge." U.S. Patent No. 6,947,621. 20 Sep. 2005.

17. Bell Jr, Raymond Mark, et al. "Waveguide-based optical interferometer." U.S. Patent No. 7,003,186. 21 Feb. 2006.
18. Acton, D. Scott, et al. "Wavefront sensing and controls for the James Webb Space Telescope." *Space Telescopes and Instrumentation 2012: Optical, Infrared, and Millimeter Wave*. Vol. 8442. International Society for Optics and Photonics, 2012.
19. Feinberg, Lee D., et al. "James Webb Space Telescope optical telescope element mirror development history and results." *Space Telescopes and Instrumentation 2012: Optical, Infrared, and Millimeter Wave*. Vol. 8442. International Society for Optics and Photonics, 2012.Redding, D. C., et al, Aerospace Conference Vol. 4-1729, IEEE, 0-7803-7651-X/03 (2003).
20. L. Feinberg, et al, UV/Optical/IR Space Telescopes: Innovative Technologies and Concepts III, SPIE, 6687-08 (2008).
21. LOWFS: Shi, Fang, et al. "Low order wavefront sensing and control for WFIRST-AFTA coronagraph." *Techniques and Instrumentation for Detection of Exoplanets VII*. Vol. 9605. International Society for Optics and Photonics, 2015.
22. Zernike, Frits. "Phase contrast, a new method for the microscopic observation of transparent objects part II." *Physica* 9.10 (1942): 974-986.
23. Redding, David, et al. "HabEx Lite: a starshade-only habitable exoplanet imager alternative." *Space Telescopes and Instrumentation 2018: Optical, Infrared, and Millimeter Wave*. Vol. 10698. International Society for Optics and Photonics, 2018.
24. Personal communications with E. Cady (JPL)