HabEx Lite: a Starshade-only Habitable Exoplanet Imager Alternative

David Redding, Keith Coste, Otto Polanco, Michael Rodgers, Claudia Pineda, Kevin Hurd, Howard Tseng, Jose Quezada, Stefan Martin, Joel Nissen, Kevin Schulz, Jonathan Tesch, Eric Cady
Jet Propulsion Lab, California Institute of Technology
4800 Oak Grove Drive, Pasadena CA 91109

Michael Rodgers
Synopsys

Matthew East, James Mooney
Harris Inc.

Chris Stark
Space Telescope Science Institute

ABSTRACT

The HabEx mission concept is intended to directly image planetary systems around nearby stars, and to perform a wide range of general astrophysics and solar system observations. Its main goal is the discovery and characterization of Earth-like exoplanets through high-contrast imaging and spectroscopy. The baseline HabEx concept would use both a coronagraph and a starshade for exoplanet science. We describe an alternative, "HabEx Lite" concept, which would use a starshade (only) for exoplanet science. The benefit is lower cost: by deleting the complex coronagraph instrument; by lowering observatory mass; by relaxing tolerances and stability requirements; by permitting use of a compact on-axis telescope design; by use of a smaller launch vehicle. The scientific penalty of this lower cost option is a smaller number of detected exoplanets of all types, including exoEarth candidates, and a smaller fraction of exoplanets with measured orbits. Our approach uses a non-deployed segmented primary mirror, whose manufacture is within current capabilities.

1. INTRODUCTION

In 2016, NASA commissioned a study to define a Habitable Exoplanet Imager, or "HabEx" space observatory, to survey nearby solar systems to discover and characterize exoplanets. A driving scientific objective for HabEx is direct imaging of candidate exoEarths – rocky planets in the Habitable Zones of their respective stars. HabEx would conduct spectroscopic observations of these planets to characterize their atmospheres, looking for chemical signatures of possible life, such as water, oxygen, ozone, carbon dioxide and methane. HabEx would also be a highly capable general astrophysics observatory, a powerful successor to the Hubble Space telescope, with diffraction-limited imaging and high-resolution spectroscopy covering the Far Ultra-Violet through the Near IR wave bands. UV spectroscopy of the gasses in and between galaxies will trace the life cycle of baryons; multiband imaging of resolved stellar populations in nearby galaxies will identify their star formation histories; solar system observations would enable study of a wide range of planetary characteristics. These are just some of the potential programs being defined for HabEx by its Science and Technology Definition Team (STDT)[1,2,3].

The HabEx study is developing three distinct concepts for its space telescope observatory, representing different price/performance design points. The baseline HabEx Architecture A design concept uses a 4-meter, off-axis, unobscured telescope optimized for coronagraph observations of exoplanets[4]. HabEx A is planned to have both a coronagraph and a starshade for its exoplanet observations: the coronagraph for its rapid retargeting capabilities, useful for surveying large numbers of systems and for multiple revisits to determine planetary orbits; and the starshade for its larger instantaneous bandpass and outer working angle, useful for obtaining spectra of exoplanets.

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This paper describes a second, Starshade-only observatory concept, HabEx Lite, which is under study as the HabEx Architecture B. HabEx Lite is a 4 meter, on-axis space telescope, using only a starshade occulter for exoplanet science, and equipped with powerful general astrophysics instruments. HabEx Lite is lower cost than HabEx A by design. Yet it should meet the threshold HabEx exoplanet science objectives, while supporting all HabEx general astrophysics objectives. The third, HabEx Architecture C design, would use only a coronagraph, so is essentially HabEx A without a starshade.

2. IMAGING EXOPLANETS

The challenge for any telescope directly observing exoplanets is to suppress the light from the star at the center of the exoplanetary system, while passing the light of the planets around it. The Sun-Earth system provides a useful example for the extrasolar planetary systems HabEx would target. Seen from a 5-parsec distance, Earth's orbit will take it as far as 200 milliarcsec (mas) away from the sun. A 4 m HabEx telescope would have a Rayleigh diffraction resolution of 50 mas at 500 nm wavelength – sufficient to distinguish the Sun and Earth if they were the same brightness. They are not – the brightness of the Earth is about $2x10^{-10}$ times that of the Sun at visible wavelengths. Some means of suppressing the starlight by about 10^{-10} (contrast) is therefore required to enable high signal-to-noise images of the planet.

One method is to use a coronagraph: an optical instrument that takes the light from the star and focuses it onto an occulting mask, where most of the starlight is suppressed[1,5]. A Lyot stop cleans up the residual light scattered by the mask, to create a "dark hole" discovery region on the focal plane. Optical aberrations in the telescope and instrument create speckles of light in the dark hole – these are suppressed using two Deformable Mirrors (DMs) in the coronagraph. Planet light comes in at a slightly different angle than the starlight, misses the mask, and falls into the dark hole, where it can be detected.

Coronagraphs can change observational targets by simply repointing the telescope, enabling them to rapidly explore and revisit many stars, speeding discovery of planets and characterization of their orbits[6]. But: coronagraphs are complex, actively controlled devices, that impose stringent design, precision and stability requirements on the telescope. The starlight suppression methods decrease the amount of planet light, and limit the bandpass of the light, that can reach the detector. And coronagraphs, once having established 10^{-10} contrast, need to maintain contrast to the 10^{-11} level – which corresponds to stabilizing the telescope and instrument wavefront to 10 picometers RMS at mid spatial frequencies.

Starshades provide a second method for high contrast imaging[7]. A starshade is a second spacecraft, shaped like a huge flat flower tens of meters wide, that is flown in precise formation tens of thousands of kilometers away from the telescope, in the direct line of sight between the telescope and the star (Fig. 1). The starshade creates a deep shadow, blocking the light from the star while passing the planet light. Starshades can have higher throughput than coronagraphs, do not require elaborate on-board speckle nulling controls, and have an Outer Working Angle limited only by the detector field. They also do not require ultra-stable optics. Depending on design choices, starshades can provide for higher image quality, covering a wider waveband than coronagraphs, for more efficient spectroscopy. But: Starshades expend significant amounts of fuel maneuvering to each new target, limiting the number of observations that can be made. This makes starshades less efficient for search and revisit than coronagraphs.

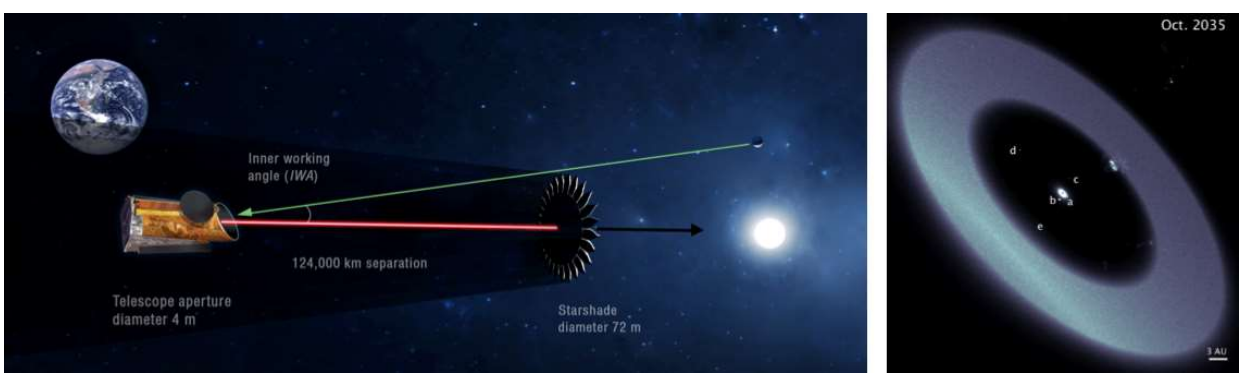


Figure 1. (*left*) High contrast imaging using a starshade, from the HabEx Interim Report[1]. (*right*) A solar system analog as seen from 5 pc by HabEx + starshade in the 12x12 arcsec field of the UV/Vis starshade Instrument channel, showing: (a) an exoEarth; (b) a sub-Neptune; (c) Jupiter, (d) Saturn, (e) Neptune; an inner dust belt (3x zodiacal dust within 1 AU); and an outer dust belt (3x Kuiper belt extending 22 to 33 AU). Credit: S. Hildebrandt.

The driving metric for missions like HabEx is "exoEarth yield[8]," the projected number of earth-like planets orbiting Sun-like stars in the Habitable Zone (where liquid water can exist on the planet's surface) that would be characterized by the mission. While the HabEx Lite mission yield has not yet been quantified, it is expected to characterize fewer exoEarths than HabEx A. Other factors, currently under study, such as starshade size and maneuverability, or the possibility of precursor surveys using ground or space-based telescopes to identify the best target systems[9], will affect the yield of both systems. The HabEx study team will provide definitive yield estimates in the HabEx final report, due in 2019.

3. HABEX LITE BASELINE DESIGN

Requirements and design approach.

Specific science objectives and the flow down to observatory requirements for HabEx are documented in the Science Traceability Matrices (STM) presented in the HabEx Interim Report[1]. A summary of top-level requirements is provided in Table 1. These specify the basic performance of the telescope and its instruments: a HabEx Workhorse Camera (HWC)[10], providing a wide range of UVOIR imaging and spectroscopy modes; a UV Spectrograph (UVS)[11], for high spectral resolution in the 115-300 nm wavebands; and a starshade Camera (SSC)[12], with a narrow field for imaging and low-resolution spectroscopy, and with pupil imaging modes to provide starshade position guiding[13].

Table 1. Key HabEx observatory requirements, summarized.

	Parameter	**Value**		**Parameter**	**Value**
General	Aperture diameter	4 meter	*Workhorse Camera*	Waveband, imaging	150-1,700 nm
	Bandpass	115–1,700 nm		Waveband, spectroscopy	350-1,400 nm
	Operating temperature, telescope optics	≥270K		Field of View	≥2.5x2.5 amin
	Diffraction limit wavelength	400 nm		Spectral resolution	R ≥2,000
	Wavefront error, total	≤30 nm rms	*UV Spectro-graph*	Waveband	115-300 nm
	Pointing accuracy	2 mas/axis		Field of View	≥2.5x2.5 amin
	Pointing stability	2 mas/axis		Spectral resolution	R ≥ 60,000
Exoplanet	Raw contrast	$\leq 10^{-10}$ from IWA	*Starshade Instrument*	Waveband, imaging	300-1,700 nm
	Inner Working Angle	<74 mas		Waveband, spectroscopy	300-1,700 nm
	Spectroscopic resolution	R≥ 7 (300–450nm)		Imaging Field of View	12x12 asec
		R≥ 140 (450nm–1um)		Spectral resolution	R ≥2,000
		R ≥ 40 (1–1.8um)		Starshade guider modes	UV and IR

The design approach for HabEx Lite is to fully implement these requirements without using a coronagraph, and to do it in a strictly cost-conscious way. Particular cost-related benefits compared to HabEx A (which uses both a starshade and a coronagraph) include:

- Not including a coronagraph eliminates an expensive, heavy and complex instrument and its electronics.
- It eliminates the requirement for the picometer-stable, telescope-plus-instrument wavefront error that a coronagraph needs to preserve contrast[5]. Imaging with a starshade does not impose any special image quality requirements beyond those needed for UVOIR imaging and spectroscopy.
- It permits use of conventional on-axis telescope configuration, with a central obscuration from the secondary mirror. The result is that HabEx Lite can fit its 4-meter aperture into an existing Delta IV Heavy launch vehicle shroud. In contrast, HabEx A uses an off-axis design that avoids the central obscuration for improved coronagraph performance, but this grows the size and mass of the telescope to the point that it must use a larger, more expensive, as-yet unflown vehicle, specifically the SLS Block 1B.
- It also allows use of a non-deployed, segmented Primary Mirror (PM) that is lower mass than the monolithic 4-meter PM planned for HabEx A. Using a segmented PM keeps the fabrication of the glass mirrors within the current state of the art.

- Taken together, these factors greatly reduce the mass of the HabEx Lite telescope compared to HabEx A. This, by ripple effect, reduces the mass of the HabEx Lite spacecraft to about half that of the HabEx A spacecraft. Past experience, and most space vehicle cost models, show that lower mass correlates to lower cost.

The scientific penalty for using a Starshade-only approach is that the number of targets that can be visited (and revisited) is reduced. This is because the starshade must maneuver long distances to reposition itself each time the observing target is changed, taking time and using maneuvering fuel, both limited resources. Fewer exoEarth discoveries can be made as a consequence. This deficiency could be partially made up, however, by flying a smaller Starshade, or by flying a second Starshade, or by performing a precursor study – a deep radial velocity survey of likely target stars – to reduce the need for random search and allow the mission to focus on the best targets[9]. Further discussion is provided below.

Optical design.

HabEx Lite is intended to provide the same basic instrument suite as the baseline HabEx A architecture, minus any coronagraph. The reader is referred to the HabEx Interim Report[1] for an in-depth discussion of the science driving the selection of these instruments, along with more implementation details. The focus in this report is on demonstrating that the HabEx A instruments can be accommodated by the more compact HabEx Lite configuration.

The most challenging instrument for HabEx Lite turns out to be the UV Spectrograph[11] (UVS), driven by the need for high optical quality at the Cassegrain focus, where a Micro Shutter Array[14] (MSA) is placed, while keeping the number of reflection as small as possible. The requirement for small PSF size at the MSA drives the PM-SM separation long, which reaches a limit when the Observatory becomes too long for the launch vehicle shroud. The requirement for a minimal number of optical surfaces is needed to maximize SNR for the shortest FUV wavelengths, given the low reflectivity of even the best UV optical coatings in the target spectral waveband, covering 115 to 300 nm wavelengths.

The solution is a Cassegrain telescope, with a Primary Mirror (PM) f/no. of 1.1, and a system f/no. of 18, as pictured in Fig. 2. The total telescope Field of View (FOV) is 0.1 degrees (6 arcmin), shared between the three instruments. This configuration preserves compatibility with the Delta IV Heavy 5-by-16.5-meter shroud volume, without requiring any telescope or sunshade barrel or scarf deployments. By using toroidal optical figure for the SM, it provides high optical quality PSFs at the off-axis Cassegrain focus for the UVS.

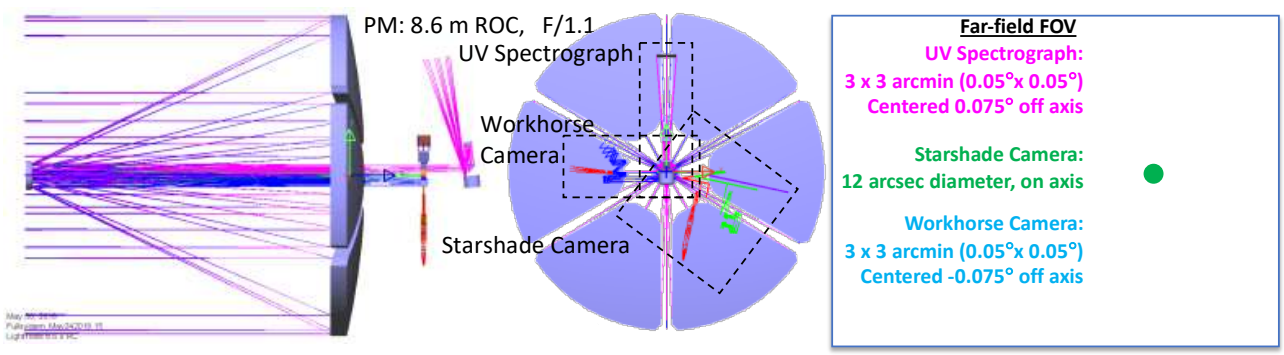


Figure 2. Optical layout, showing Cassegrain Optical Telescope Assembly (OTA), the three instruments, and their fields of view.

The UV Spectrograph instrument accepts light from the OTA at a point 0.075° off-axis, encompassing a FOV of 3x3 arcmin (Fig. 3). Selection of objects within that field is made using the MSA, with an array of commandable shutters, 200 by 100 um in size, that open to pass light from the selected areas of the FOV. To match the curved Cassegrain focus, each quadrant of the MSA will be a separate flat array, slightly tilted to match the focal surface. The maximum PSF size at the MSA is 58 um, and the likelihood that any random object in the field is not vignetted ranges from 60 to 74%[15].

Following the MSA is a Fold Mirror, needed for packaging the UVS in a form that permits future on-orbit servicing and replacement. Then comes a Reimaging Mirror, which creates an f/75 beam converging on the Focal Plane Array (FPA). Dispersion is generated using gratings in a grating wheel located in the converging beam after the Reimaging Mirror. There are 20 dispersing elements and a flat mirror provided in the grating wheel mechanism, to provide selectable bandpass and spectral resolution, enabling coverage over the full 115 to 300 nm waveband at resolutions from R = 500 to R = 60,000.

The FPA will be populated with Micro Channel Plate (MCP)[16] detectors or with Delta-Doped CCDs[17], and will require about 30,000 by 17,000 pixels to cover the full FOV[1].

UV Spectrometer instrument	
Spectral band (nm)	115-300
FOV (arc-min)	3x3
F/# at FPA	F/75
Grating	20 grating settings + 1 mirror in a wheel.
Modes	**2:** Spectrograph; imaging.

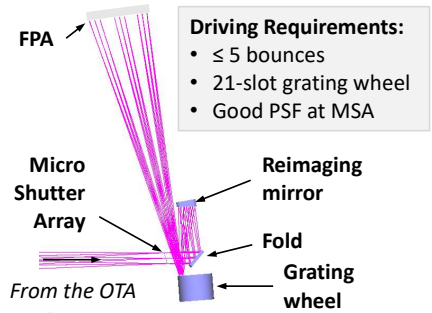


Figure 3. UV Spectrograph instrument (UVS). The grating wheel enables spectral resolutions from 500 to 60,000 covering the full 115-300 nm waveband.

The HabEx Workhorse Camera[10] (HWC) is a general-purpose instrument, providing imaging and spectrometry modes over 2 bands: a UV-Visible band covering 150 to 950 nm; and a Near IR band covering 950 to 1,800 nm wavelengths (Fig. 4). Both the UV-Vis and IR channels can observe the same 3x3 arcmin field simultaneously, as the field is shared using a dichroic beamsplitter. The switch between imaging and spectrometry modes is implemented using flip-in grisms and an insertable MSA. The spectral resolution when in spectroscopic mode is R=2000 in both channels. When in imaging mode, the MSA is commanded out of the beam to avoid vignetting. Both the UV-Vis and IR channels are equipped with filter wheels for use when imaging.

Workhorse Camera [UV-Vis and IR paths]	
Spectral bands (nm)	150-950 UV-Vis; 950-1800 IR
FOV (arc-min)	3x3
F/# at MSA	About F/18
F/# at FPA	F/40 (UV-Vis), F/21 (IR).
Modes	**4:** 2 imaging, 2 grisms.

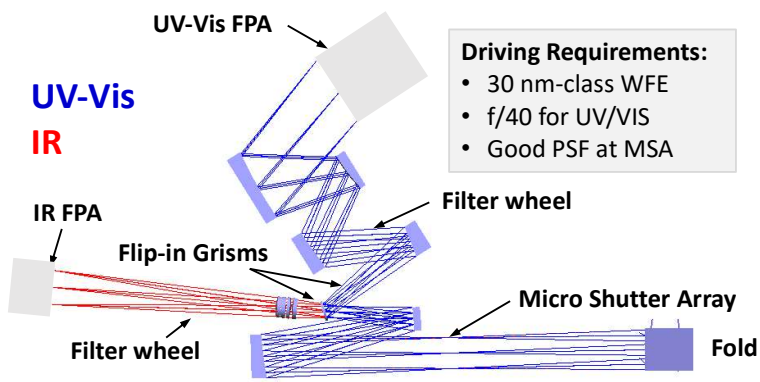


Figure 4. The HabEx Workhorse Camera (HWC), showing IR and UV/Vis channels, with imaging and spectroscopic modes.

The HWC UV-Vis channel would utilize delta-doped CCDs[17], with 12 um pixel size, mosaiced to provide a total of 12kx12k pixels. The FPA would be cooled to 153K. The NIR channel would utilize a low-noise hybrid HgCdTe/CMOS detector such as the Teledyne H4RG[18], with 12 um pixels in a 4kx4k format.

The Starshade Instrument[12] (SSI) provides separate UV, Visible and Near IR channels sharing the same 12x12 arcsec field. Each channel can be run in imaging or (narrower field) spectroscopic modes, and the UV and NIR channels also have starshade guiding modes. A typical operational configuration might utilize the UV channel in guider mode, with the PIL inserted in the beam to create a pupil image on the UV detector, while the IR and Optical channels perform imaging or spectroscopy. The 3 channels can be run simultaneously. Selection of modes within each channel is done using insertable devices: selector mirrors for the Optical and IR channels to send the light to the imaging FPA or through the respective IFS optics; Pupil Imaging Lenses (PILs) in the IR and UV channels, and the UV channel has an insertable grism.

Wavefront Error Budget.

The overall optical performance requirement from Table 1 is for total system Wavefront Error (WFE) of 30 nm RMS, in imaging modes in the HWC and SSC, consistent with diffraction limited imaging at a wavelength of 400 nm. This

requirement in turn flows down to the various subsystems in the observatory, allocating a portion of the total WFE to the OTA, and a portion to the instruments. Since HabEx Lite utilizes a segmented primary mirror which will be phased up using active Wavefront Sensing and Control (WFSC) methods, WFSC is also allocated a portion of the total WFE. There is also a distinction to be drawn between static WFE, which do not change over time once the telescope is phased up after launch, and drift WFE, which refers to the things that do change over slow time scales. The allocation of the system WFE to the subsystems is captured in the WFE Budget of Fig. 10.

Starshade Instrument [UV, Vis, and IR paths, for science and SS guiding]	
Spectral bands (nm)	200-450 UV; 450-1000 Vis; 975-1800 IR.
FOV (arcsec diameter)	12 UV, 12 Vis, 12 IR.
F/# , imaging	80 UV, 71 Vis, 51 IR.
F/#, IFS	6.0 Vis, 3.36 IR.
Modes	**8:** 3 star imaging, 2 pupil imaging (UV and IR), 2 IFS (Vis and IR), 1 spectrograph (UV)

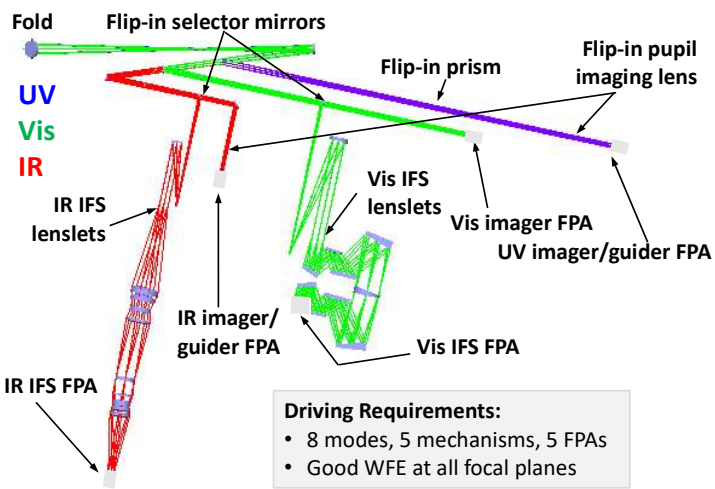


Figure 5. Starshade Instrument, showing IR, Vis and UV channels, with imaging and spectroscopic modes. The IR and UV channels also are equipped with flip-in Pupil Imaging Lenses

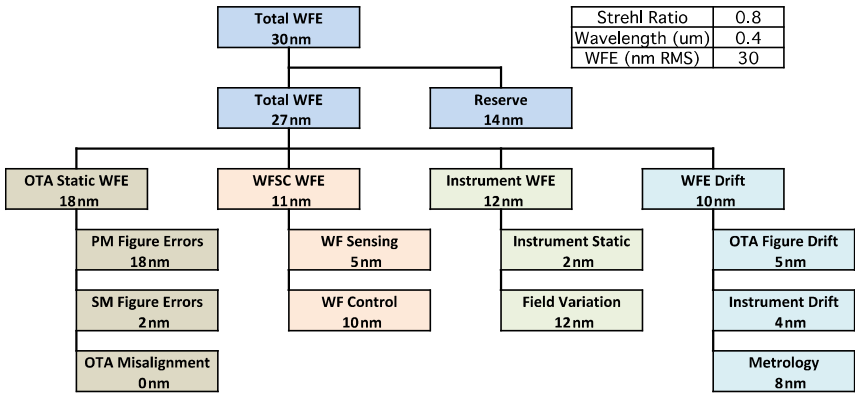


Figure 6. Wavefront error budget, showing allocations for WFE

Note that this is a post-WFSC budget, where the allocated levels of WFE include the compensating effects of the WFSC system, which measures the system WFSC and corrects it, by realigning the PM segments and the SM, and by tuning the PM segment optical figure using deforming actuators. Thus, the OTA Misalignment WFE allocation is 0 nm, since the alignment errors are controlled. Residual alignment errors, due to imperfections in the WFSC control process, are bookkept in the WFSC errors column, which totals 11 nm. Similarly, the Drift WFE includes the compensating effects of the Laser Truss Metrology system, which makes continuous nm-precision measurements of the optics, and feeds back low bandwidth corrections to the WF Control actuators, to preserve the alignments established by the WFSC system. Further details of the WFSC systems are provided below.

Note also that the largest contributor to the WFE budget is the OTA Static Figure Error, at 18 nm, driven by the post-WFSC residual PM segment figure errors. This allocation is consistent with demonstrated performance of ULE glass mirrors manufactured by Harris, Inc.[19,20,21]. These mirrors are about the size of the HabEx Lite segments, at 1.4 m (vs. 1.7 m) size. They are also light weight, at 10 kg/m^2. They are lighter than HabEx Lite mirrors, which will likely be 20 kg/m^2

for improved stiffness, with a first free-free mode frequency >300 Hz. They have demonstrated figure errors consistent with the 18 nm WFE allocation, with individual mirrors measured at 15 nm RMS, with projected post-WFSC performance of 8 nm RMS.

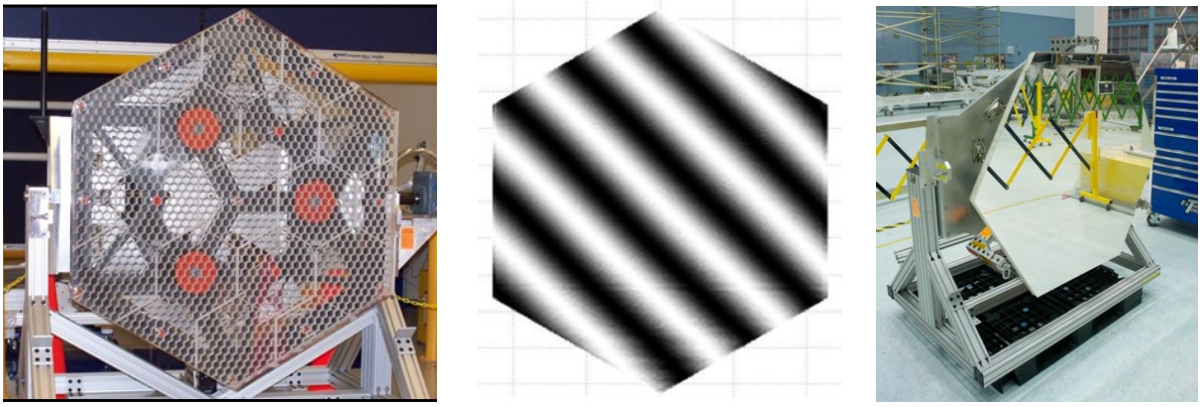


Figure 7. Ultra-low expansion glass mirrors fabricated by Harris, Inc., following the methods described in Mooney et al[19,20]. These mirrors: have demonstrated WFE performance without actuation (single mirror) of 15 nm RMS, with gravity effects backed out; are projected to meet 8 nm RMS WFE with Figure Control Actuation; have passed shock and vibration tests sufficient to demonstrate launch survivability for the glass substrate.

A notional design for HabEx Lite segments made using the Harris methods[19,20,21] is shown in Fig. 8 (left side), and the projected PM segment static figure error budget is summarized in Fig. 8 (right side). Note that there are 23 Figure Control Actuators (FCAs) between the glass substrate and an underlying reaction structure. These act to correct figure errors due to fabrication errors, such as imperfect radius-of-curvature matching, testing errors, imperfect prediction of zero-gravity figure, differences in operating and fabrication temperature, coating stresses, and polishing residuals. The error budget also includes the effects of mirror mounts and other attachments, material creep in adhesive layers, etc.

The use of FCAs enables a 7x relaxation in the mirror fabrication specifications. As shown, the performance needed to meet a 9 nm Surface Figure Error (SFE), which is consistent with the 18 nm PM segment WFE allocation, can be achieved with a glass substrate that has a total SFE of 56 nm RMS. This is a significant easing of the glass mirror specifications, and will enable lower cost, faster fabrication, using current state-of-the-practice methods. The use of FCAs also provides insurance against unanticipated WFE exceedances, in the PM segments or elsewhere in the beam train. This lowers the overall mission performance risk.

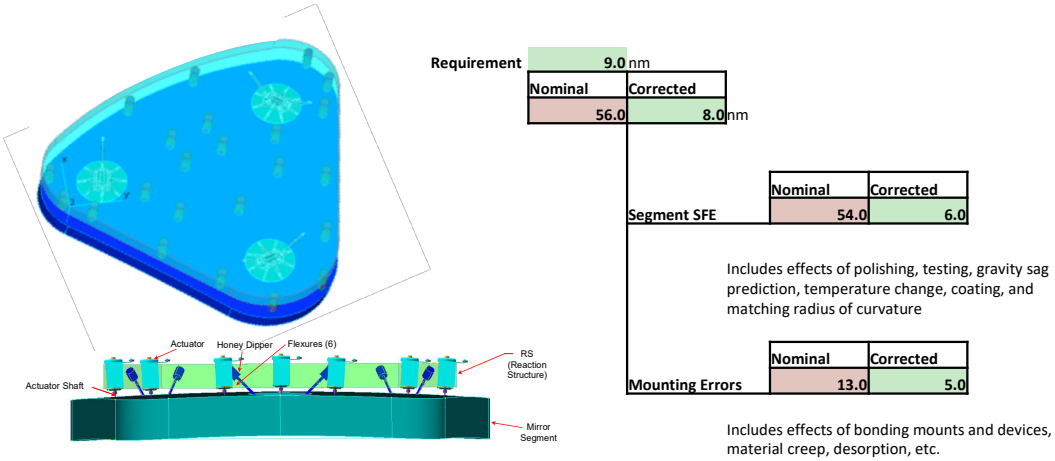


Figure 8. (*left*) HabEx Lite primary mirror segment design, showing the glass mirror substrate attached to its reaction body support structure via struts and FCAs. The reaction body is in turn attached to Aft Metering Structure (AMS) by Rigid Body Actuators (RBAs). (*right*) Mirror Surface Figure Error (SFE) budget, summing to 8 nm RMS, which converts to 16 nm RMS WFE.

It would be possible, with additional investment, to improve mirror fabrication processes to meet the tight 18 nm PM segment figure specifications without the FCAs. This would reduce the mass and complexity of the mirror systems – but it would also remove the ability to correct unanticipated WF errors. For this study, the FCAs are included in all mass estimates, along with the mirror substrates, mounts and other attached hardware, electronics and cabling.

Mechanical configuration.

The HabEx Lite telescope mechanical design approach is illustrated in Fig. 9. As shown, the PM segments are placed in pairs between the SM Support Struts. The segments are slightly asymmetric, with a small gap between adjacent segments, and a larger gap on the sides adjacent to the struts. The segments are mounted to the Aft Metering Structure (AMS) via RBAs. Adjacent pairs of segments are surrounded by a thermal "bathtub" structure, which insulates the segments and blocks direct view of space from the uncoated segment edges (Fig. 10). The thermal bathtubs also support film heaters and temperature sensors that are used to keep mirror temperatures at about 270K, and stable to ~±1 mK.

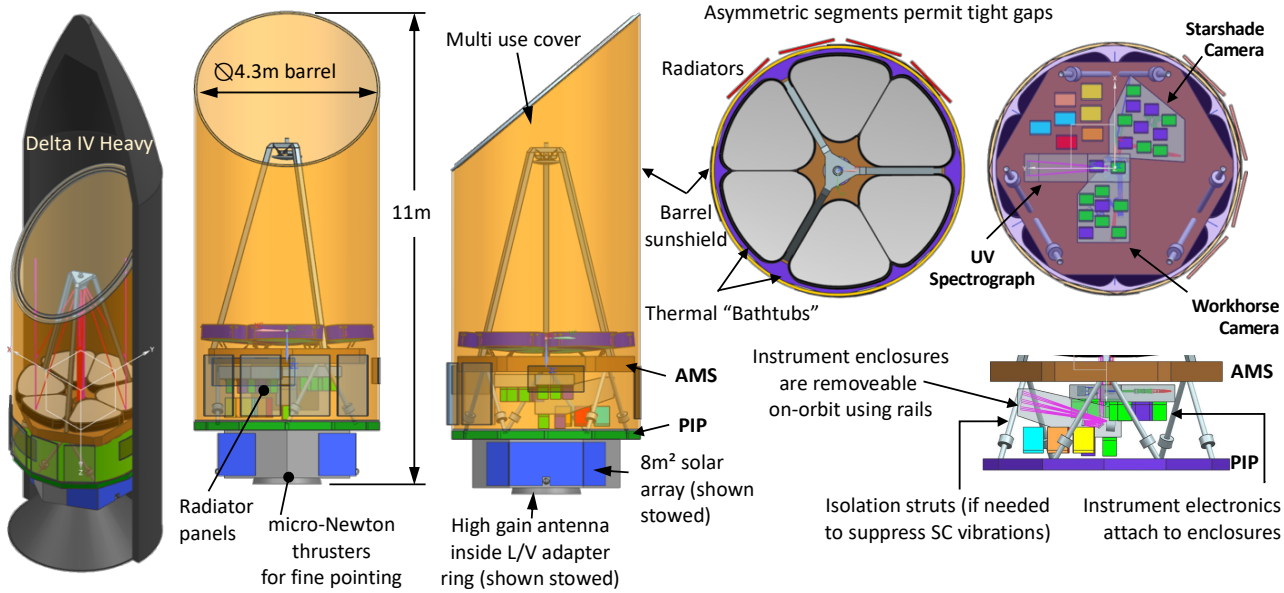


Figure 9. HabEx Lite concept mechanical configuration.

The SM support struts are also mounted directly to the AMS, as are each of the instruments. Then the AMS is attached by vibration isolation struts to the Payload Interface Plate (PIP), which forms a modular interface to the space vehicle bus. The instrument enclosures are to be provided with rails, so they can be removed on orbit, for servicing or replacement. The instrument electronics are notionally attached to the instrument enclosures, so that they can easily be removed as well. Other payload electronics are attached directly to the PIP.

The telescope is surrounded by a barrel sunshade, which is scarfed at a 40° angle, to permit observations close to the sun. The barrel is provided with a multi-use cover, which would be opened during on-orbit commissioning, and closed during potential future servicing operations. The barrel attaches to the PIP, not the AMS, to avoid distorting the optical bench. The barrel is to be equipped with servicing doors through which the instruments can be removed by robotic or teleoperated on-orbit servicing tools. The short, anti-sun side of the barrel provides support for radiators, totaling about 7 m^2 in area.

A notional spacecraft structure is shown attached to the PIP. The spacecraft is nominally a modified commercial space craft bus, configured to support the mass of the HabEx Lite observatory, and providing power, communications, telemetry, data storage, navigation, attitude control, and all the other functions needed to support the payload. Following the HabEx A approach, HabEx Lite could utilize reaction control thrusters for pointing control, with micro-Newton colloidal thrusters for fine pointing control[22], and higher-thrust chemical or electric thrusters for rapid repointing and station keeping. If that proves difficult or expensive, conventional reaction wheels could be used for pointing control.

Thermal system.

The thermal system is sketched in Fig. 10, which sketches the notional locations of heaters, sensors, instruments and the heat straps and heat pipes connecting critical items to the radiators mounted on the sunshade barrel. This preliminary approach implements passive cooling, augmented by cryocoolers for the instrument detectors. Preliminary thermal power consumption is estimated to be 330 W continuous power for the PM and SM, and 276 W for heaters on the AMS. The power required for instrument focal plane cryocoolers would be about 330 W. The solar array area required for the heaters alone is estimated to be 2.5 m^2. The radiator area required is split, with 4.2 m^2 at 20C temperature, and 2.7 m^2 at -80C.

These power numbers – 330 W for the PM and SM – are significantly less than the 3,450 W reported for HabEx A, which takes a different approach to thermal control, including heating the barrel above the PM to provide radiative heating of the PM[1]. Lower power means less solar array area and a less expensive thermal system.

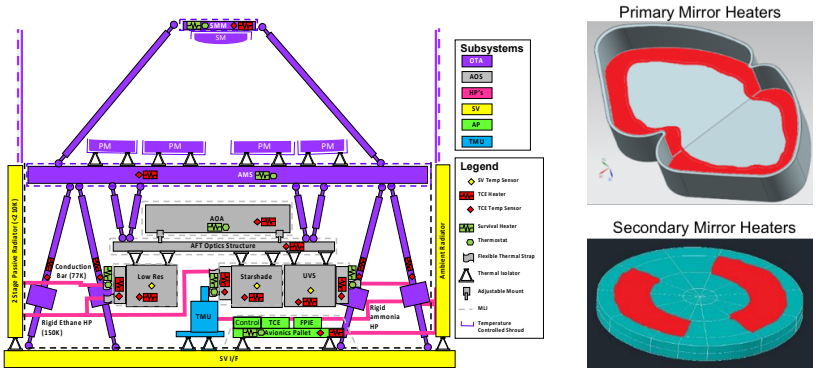


Figure 10. Thermal subsystem diagram, showing disposition of heaters, coolers, heat pipes, and radiators. Also shown at right is the preliminary location of film heaters in the PM segment thermal bathtub (3 zones), and on the SM enclosure (2 zones).

Wavefront sensing and control.

The HabEx Lite segmented PM would be launched with all segments and the Secondary Mirror (SM) in place, but secured using launch locks or snubbers. After launch, the segment and SM RBAs would be used to place all optics near their optimal positions. Final adjustments will be implemented using image-based Wavefront Sensing and Control (WFSC) techniques. While pointing at a bright guide star, a sequence of imaging operations would: (1) capture the light from each segment; (2) coarsely align each segment and the PM; (3) phase the segments to each other using broad-band dispersed-fringe phasing techniques; and (4) use high-resolution phase retrieval measurements of the WFE in each instrument to make final adjustments to the RBAs and FCAs, to establish diffraction-limited imaging in all channels. For this telescope initialization process, HabEx Lite would use mature WFSC technologies developed for James Webb Space Telescope (JWST) [23,24,25].

HabEx A as described in the Interim Report[1] is planning to use continuous high bandwidth Laser Truss Metrology (MET) to maintain alignments between the PM, SM and back-end instrument optics. HabEx Lite would also use MET, coupled with precision rigid body actuation, to stabilize the pose (position and orientation) of the PM segments and the SM with respect to the instruments. Closed-loop MET control of the alignment states of the observatory, as diagrammed in Fig. 11, would fully stabilize the entire optical train, preserving diffraction-limited performance throughout all operations.

Laser metrology draws its heritage ultimately from the Space Interferometry Mission (SIM) project, which demonstrated picometer precision on large ground-based testbeds, with large and heavy beam launchers and corner cubes. Subsequent development achieved much smaller and more compact laser metrology devices for attachment to lightweight mirror segments, targeting performance at the sub-nanometer level[26]. The LISA Pathfinder mission has further refined laser metrology technology, flying laser gauges and electronics that demonstrated picometer accuracy. Combining elements of the SIM and LISA approaches would provide the picometer-precision alignment measurements that LUVOIR will need to preserve coronagraph high contrast performance during extended observations, and do it in a compact, unobtrusive package that would not interfere with image quality.

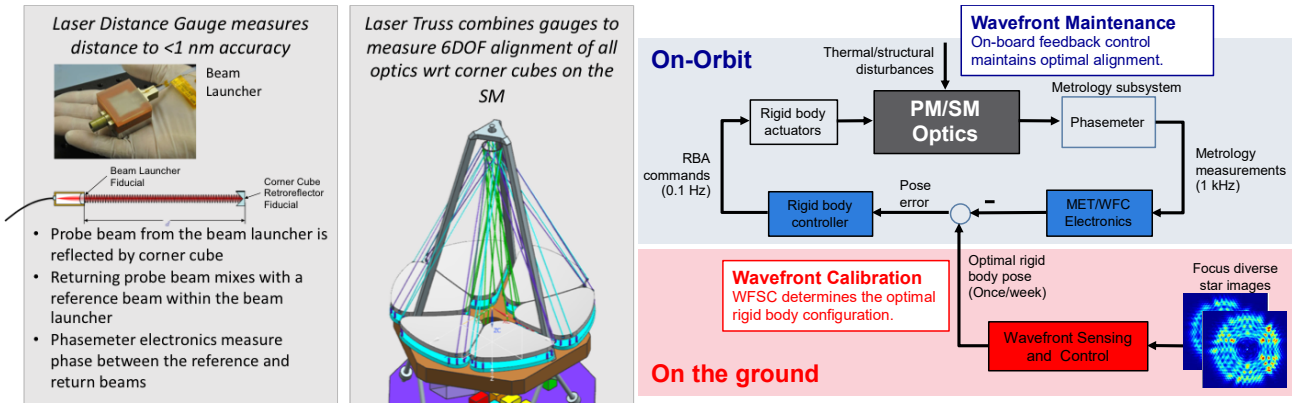


Figure 11. Wavefront Sensing and Control overview, showing the MET system used to stabilize the telescope.

Configuration summary.

The HabEx Lite design was developed in CAD software, which also mass estimates for each modeled element. This information, together with estimated masses for other normal space mission elements, was accumulated using standard methods, and is summarized in Table 2. As shown, the total Current Best Estimate (CBE) for the observatory payload is 3471.5 kg. Following standard practice, this preliminary estimate is multiplied by an uncertainty factor of 1.43, yielding a CBE mass + uncertainty of 4987.3 kg total payload mass. Combined with preliminary estimates for the spacecraft bus, launch adapter, propellant and pressurant, the total mass + uncertainty for the entire HabEx space system is 9420 kg. This compares to the Delta IV Heavy launch capability to L2 orbit of 10,000 kg. Total margin against launch capability (LV capability – CBE launch wet mass) is 3428.5 kg, or 34.28%.

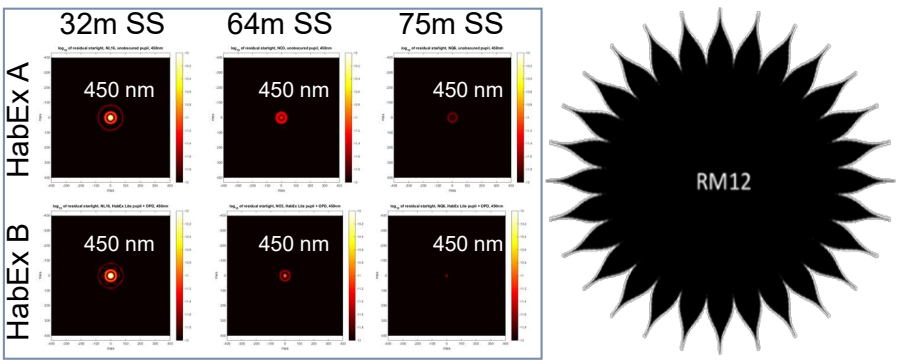
Table 2. Master Equipment List.

Element Name	ASM PARENT	Qty	Material	CBE Mass /Unit (Kg)	CBE MASS (kg)	JPL Uncertainty Factor	CBE Mass+JPL Uncertainty Factor
HABEX SEGMENT TELESCOPE Assembly (4m--6 Segment)	HABEX ASM	1			**3471.5**	**1.43**	**4987.3**
Primary Mirror Assembly	HABEX ASM	1			404	1.43	578.3
Secondary Mirror Assembly	HABEX ASM	1			109	1.43	155.6
UV Spectrograph	HABEX ASM	1			147	1.43	209.5
Workhorse Camera	HABEX ASM	1			203	1.43	290.2
Starshade Camera	HABEX ASM	1			238	1.43	340.0
Electronics Assembly	HABEX ASM	1			164	1.43	234.1
Aft Metering Structure (AMS) Assmebly	HABEX ASM	1			456	1.43	652.1
Secondary Support Assembly	HABEX ASM	1			195	1.43	279.5
Barrel Assembly	HABEX ASM	1			753	1.43	1076.7
Radiator Assembly	HABEX ASM	1			315	1.43	450.5
Telescope to SC Strut Assembly	HABEX ASM	1			142	1.43	202.7
Cabling Assembly	HABEX ASM	12			328	1.5	492.3
Dust Cover Assembly	HABEX ASM	1			18	1.43	25.7
Spacecraft Bus Assembly					**2050**	**1.43**	**2932**
Launch Vehicle Assembly					**1050**	**1.43**	**1502**
Hydrazine	LAUNCH VEHICLE ASM	1		400.000	400	1.43	572
Xenon	LAUNCH VEHICLE ASM	1		200.000	200	1.43	286
Launch Dry Mass (inc. LV Interface)					5972		8562
BOL Mass (post Transfer Orbit)					6122		8777
Launch Wet Mass				**6571.535**	6572		9420
LV Capability (***Delta IV, M+(5,4)) @ SEL2)***					10000		10000
Total Margin (LV Capability-Launch Wet Mass)							**3428.47**
Total Margin % of LV Capability							**34.28%**

This mass is approximately half of the mass of HabEx A as described in the HabEx Interim Report[1]. While this paper does not attempt to provide a cost estimate for HabEx Lite, past experience, and most space vehicle cost models, show that lower mass correlates to lower cost.

4. STARSHADE PERFORMANCE

How well does the segmented HabEx Lite aperture perform in its critical starshade observations? To assess this, simulations comparing its high-contrast imaging performance with the unobscured HabEx A aperture were performed[27], with results shown in Fig. 12. As indicated, HabEx Lite starshade contrast and Inner Working Angle are essentially the same as for the unobscured HabEx A. Throughput is reduced <10% by the slightly smaller collecting area of the segmented aperture. The key performance parameters – the Inner Working Angle, contrast and throughput – all meet HabEx goals. In addition, the other key virtues of the starshade method are fully retained. Unlike the coronagraph, there is no Outer Working Angle with a Starshade, so the high contrast detection region in the focal plane extends to the edge of the focal plane field of view, 12 x 12 asec for the SSI imaging modes. And, for spectral observations, the starshade method permits full bandpass observations in all channels simultaneously, at full telescope throughput.



HabEx Starshade

Name	RM12	*preliminary*
Diameter	72m	52m
Petal Length	16m	16m
Minimum F	10	8.8
Bandpass	150-500nm	150-500nm
IWA	30mas	35mas
Distance	251,519 km	153,200 km
Bandpass	300-1000nm	300-1000nm
IWA	60mas	70mas
Distance	125,760 km	76,600 km

Figure 12. (*left*) HabEx starshade contrast performance against different starshade designs, showing that HabEx A and B have the same overall contrast performance. HabEx throughput is lower by <10%, due to its slightly smaller collecting area. (*center*) Planform drawing of the 72 m RM12 Starshade. (*right*) Performance of RM12 and a preliminary design for a smaller, more agile starshade alternative in 2 different spectral regimes.

Also shown in Fig. 12 is a planform view of a 72-meter Starshade, and a table comparing the performance of the 72 m starshade to the performance of a preliminary, 52-meter starshade design[28]. The smaller starshade has the advantage that it is more maneuverable, as indicated in the shorter separation distances noted in the table. Ongoing work will consider if this slightly more aggressive design will be able to provide HabEx with higher overall exoEarth yield numbers.

The exoEarth yield performance of a Starshade-only HabEx mission would also benefit by knowing where to look[9]. Precursor surveys of nearby solar systems using improved, ultra-sensitive radial velocity techniques could identify target systems in advance, perhaps even identifying Earth-like planets and their orbits. This possibility will also be considered as part of the larger HabEx study and documented in the final report.

5. CONCLUSIONS

HabEx Lite shows a technical path to achieving the threshold scientific goals of the HabEx mission study at a lower cost than the full HabEx A baseline mission concept. The cost savings come about: by not using a coronagraph; by avoiding the challenging picometer-level stability requirements a coronagraph requires; by use of a compact on-axis telescope design to enable the spacecraft to fit into a smaller launch vehicle; by use of a smaller launch vehicle; by using a lower-mass segmented primary mirror whose manufacture is within the current state of the art; and by using efficient thermal control methods to reduce power demand. Overall mass of HabEx Lite is projected to be about half of that of HabEx A.

The downside of this approach is the loss of the observational agility provided by the HabEx A coronagraph, which would enable searching more planetary systems, and which would be more efficient at determining orbits of planets once discovered. The full value of the starshade is preserved, however: smaller Inner Working Angle; no Outer Working Angle; and full telescope throughput and bandpass for spectroscopic observations. The scientific cost would be a smaller number

of discovered candidate exoEarth planets. This cost could be reduced if precursor high-sensitivity RV surveys are conducted, to aid in identification of the best targets for starshade observation. Exactly how many exoEarths would be discoverable remains a work in progress, which will be documented in the HabEx final report.

No reduction in general astrophysics and solar system science is expected, except for coronagraph observations of non-stellar objects – these could be observed using the Starshade, but only in competition with the exoplanet science program. In fact, it is expected that more time would be available for general observatory science without the coronagraph.

6. ACKNOWLEDGEMENTS

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