Beyond JWST: Technology Path to a High Definition Space Telescope

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High Definition Space Telescope (HDST)

- A 10-12 meter aperture UVOIR space telescope, with resolution of 100 pc everywhere in the visible universe
- Equipped with a coronagraph for direct imaging of exoplanets, for discovery and characterization of tens of exoEarths

- *A feasible, streamlined concept with:*
  - A segmented, deployable mirror in a warm telescope
  - Diffraction-limited performance at visible wavelengths
  - Full complement of coronagraphic, imaging, and spectroscopic instruments
  - Covering UV to near-IR wavelengths
  - Photon-counting detectors in gigapixel arrays

Coronagraphy and Segmented Apertures

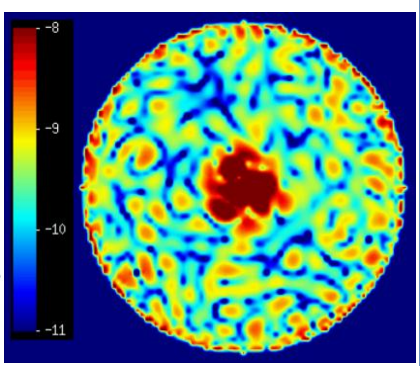
*In the TPF days, it was assumed that high contrast (>1e9) imaging required an unobscured, monolithic pupil **… but recent research shows that segmented apertures can indeed be used for high contrast imaging***

WFIRST-AFTA success story

By combining wavefront control and coronagraph design, high performance solutions have been identified for an “unfriendly” aperture (large central obstruction + spiders)

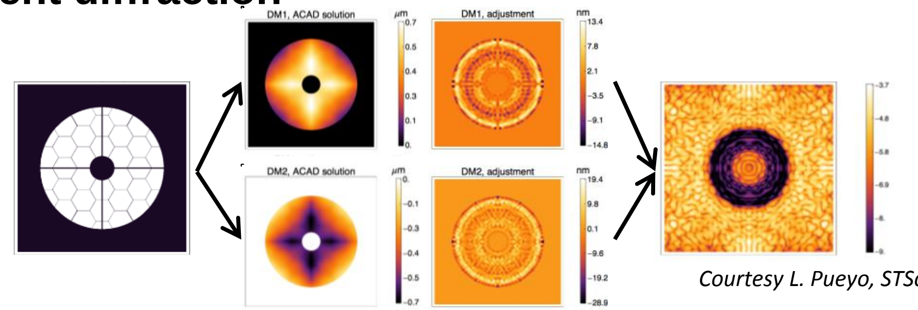
3 solutions are now being pursued: HLC & SPC (baseline) and PIAACMC

2.4-m telescope assembly



WFIRST-AFTA HLC simulated image (J. Krist, JPL)

Wavefront control can significantly reduce residual segment diffraction

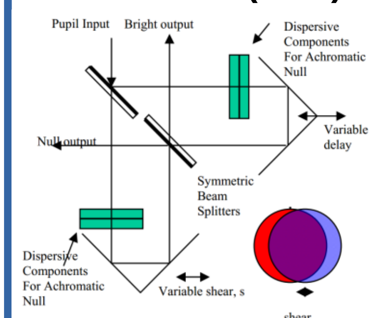


Courtesy L. Pueyo, STScI

ACAD: 2 DMs are used to shape the starlight, suppressing speckles and controlling diffraction scatter to create a high contrast “dark hole”

Coronagraph solutions exist that are, by construction, fully insensitive to pupil segmentation

Visible Nulling Coronagraph (VNC)

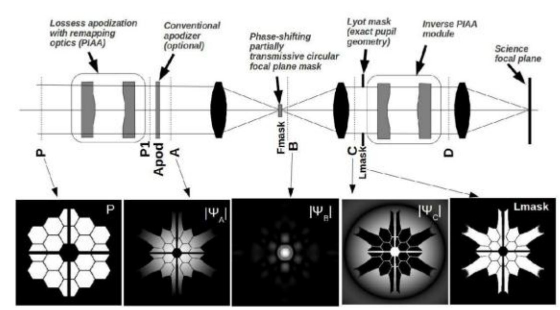


VNC is a shearing nulling interferometer

Shear can be set to an integer number of segments

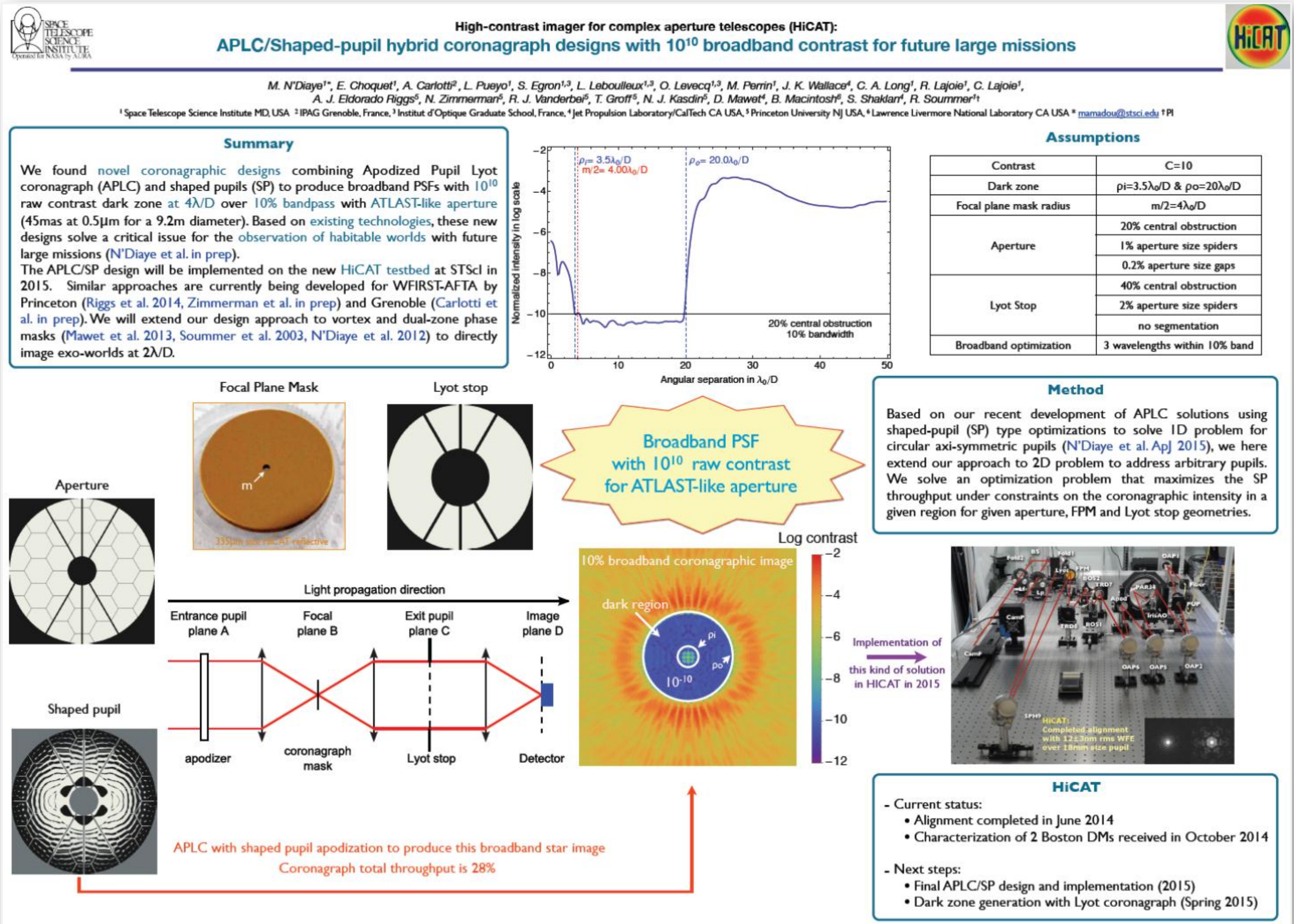
PIAACMC

Produces full suppression with 100% throughput for any pupil shape



More on Segmented, Obscured Aperture Coronagraphy...

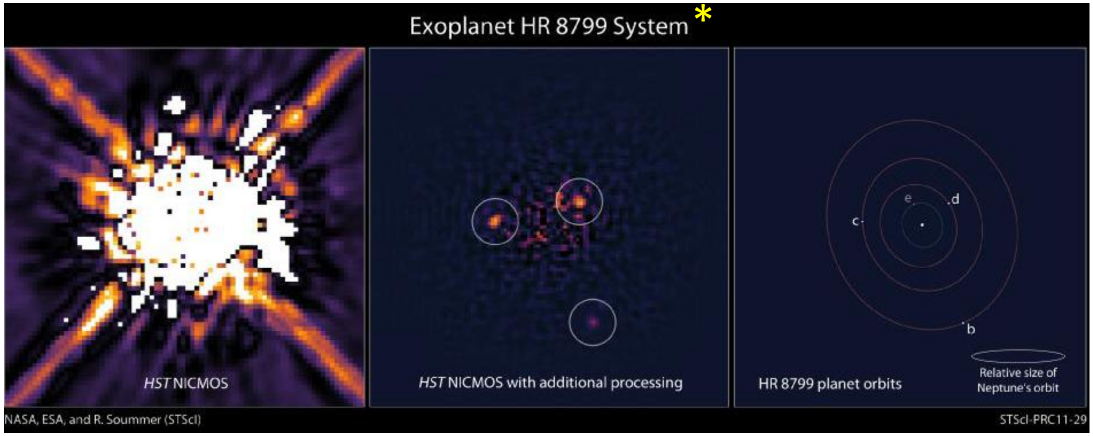
- 338.26, Wednesday: *Laurent Pueyo et al*, “High contrast imaging with an arbitrary aperture: active correction of aperture discontinuities: fundamental limits and practical trades offs.”
- 258.09, Tuesday: *Mamadou N'Diaye et al,* “APLC/Shaped-pupil hybrid coronagraph designs with 10^{10} broadband contrast for future large missions.”



Coronagraph Contrast Performance

- Inner Working Angle (IWA) < 30/50 mas (at 0.6/1 μm) – *within the Sun-Earth separation as seen from 20 parsecs distance*
  - Coronagraph IWA: *< 2.5 λ/D for D = 10 m at λ = 1 um; <3 λ/D for D = 12 m*

- Detection Contrast < 10^{-10} – *combining raw contrast and PSF calibration and subtraction*
  - Raw Contrast ~10^{-9} → *demonstrated on subscale unobscured coronagraphs*
    - Consistent with predicted AFTA Coronagraph obscured aperture performance → *soon to be demonstrated*
  - PSF Subtraction: 10x to 30x contrast improvement
    - Exploiting techniques developed for HST high dynamic-range imaging (and ground-based observatories)
    - Roll calibration and other speckle identification methods will provide further contrast improvement



WFIRST/AFTA, HST and ExEP heritage provides a strong foundation for HDST.
Needed: *coronagraph studies for 10-12 m, segmented, obscured aperture HDST*

*Ref. R. Soummer, STScI

Ultra-Stability

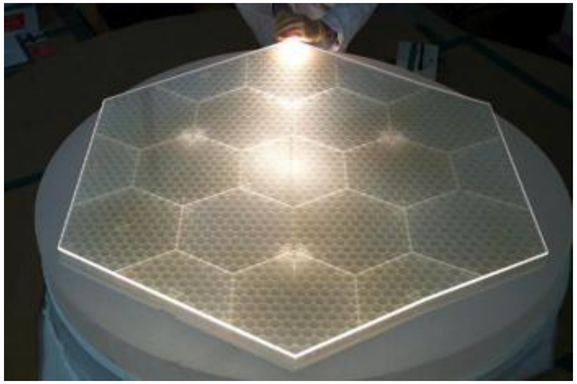
- Raw contrast of 10^{-9} to 10^{-10} requires ~10 picometer stability of the combined telescope and coronagraph wavefront*
- Doable with a multi-tiered approach, some combination of:
  - Passive thermal control: L2 orbit, flat-plate sunshield, long-dwell observations → *JWST heritage*
  - Active thermal control of optics (and structures) → *< 1 mK performance needs to be demonstrated*
  - Vibration suppression → *industry-developed non-contact isolation*
  - Continuous Speckle Nulling, at very low BW
  - Continuous Wavefront Sensing, using in- and out-of-band light → *builds on the developing AFTA Coronagraph LOWFS technology*
  - Picometer laser metrology→ *SIM and non-NASA heritage < 1 nm*
  - Small Deformable Mirrors: corrector mirrors in the coronagraph → *also consider segmented DMs and active PM segments*

Needed: System-level design for ultra-stability, and the key device technologies

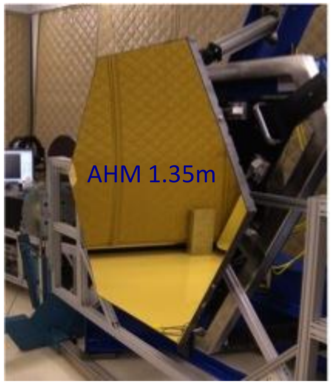
*Ref. S. Shaklan, JPL

Mirrors

- *Primary Mirror systems* for a 10-12 m HDST benefit from NASA and non-NASA heritage
- Systems include substrates, passive and active thermal control, and (most likely) some level of figure control



AMSD Lightweight ULE Segment Substrate



AHM SiC-based Segment Substrate

- Key challenges include:
  - Diffraction-limited optical quality → *demonstrated*
  - UV compatibility (μroughness, contamination, …)
  - Low cost, low mass, and rapid fabrication
- Trades include:
  - Thermal control approach (low CTE vs. high conductivity)
  - Level of figure control

<u>Needed</u>: mirror system wavefront stability to 10 picometers per 10 minutes – and the ability to measure this level of performance

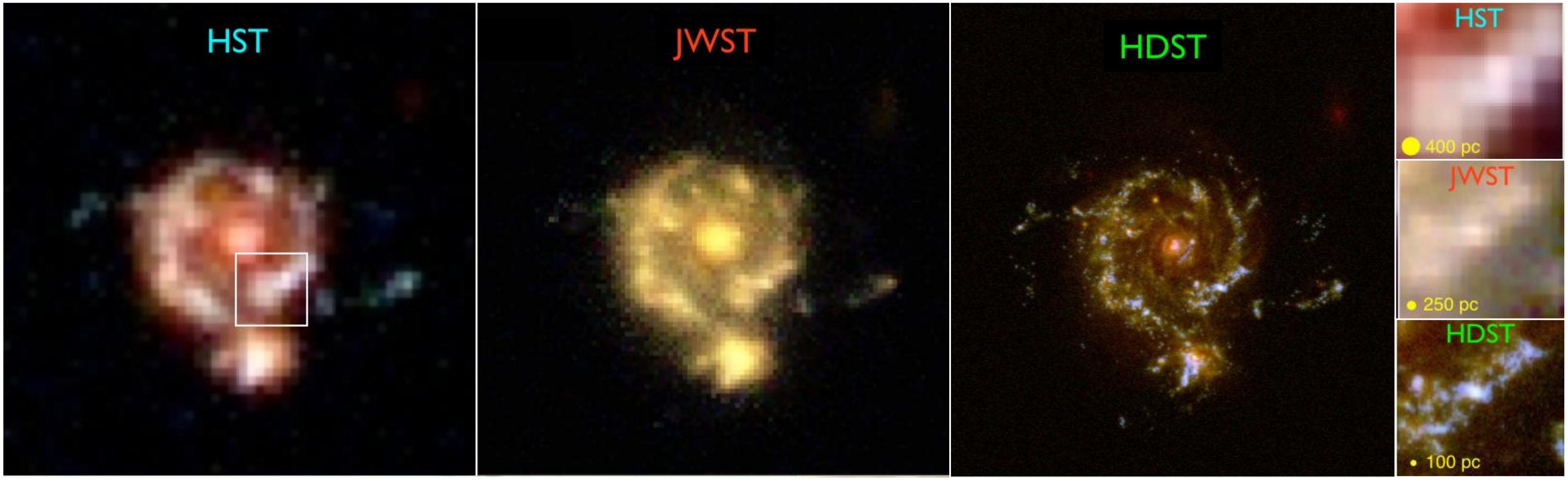
Starshades

- An HDST-optimized starshade would have:*
  - A diameter of 80 m, with petals ~20 m long, for Fr = 12
  - A distance from the HDST telescope of 160,000 km
  - IWA of 50 mas for $\lambda \leq 1$ um, and 100 mas for $\lambda \leq 2$ um
  - ~100% throughput (vs. 10-30% projected for coronagraph)
  - Wide bandpass (vs. 10-20% projected for coronagraph)
- Starshades are better than coronagraphs for deep spectral characterization, but retargeting time is likely to be days to weeks
- ExEP and Exo-S Probe studies have developed many key elements for ~40 m-class Starshades
  - Edge control, deployment, etc.
- Chief challenge for HDST is a design for an 80 m-class Starshade → *candidate for on-orbit construction? or stop down and use a smaller Starshade? or Fr < 10?*
- <u>*Needed*</u>*: exoEarth yield analysis incorporating a Starshade, either stand-alone or as a complement to a survey-optimized coronagraph*

*Ref. S. Shaklan, JPL

Starshades provide an alternative in case coronagraphs fall short, and a potentially useful complement for deeper characterization of identified exoEarths

Maximizing Sensitivity and Throughput, FUV to NIR



- "Photon counting detectors" - Low read noise and dark current
  - Exo-Earth Spectroscopy: Count rate per pixel requires ultra-low noise detectors in Vis/NIR
  - UV General Astrophysics – sensitivity boost
- Coatings: enhancing across the board throughput
  - Broadband, UV-NIR coatings with high R down to 92 nm
  - Possible impact of enhanced coatings on WFE being assessed

__Needed__: ultra-low noise, photon counting detectors in the visible and near IR

Highest Priority Technologies

Technology Needed for HDST				Current Status			
Technology Category	*Technology*	*Performance Goal*	*Details*	*Heritage*	*Current Performance*	*Maturity of Goal Perf.*	*Priority*
Coronagraph	Segmented Aperture Coronagraphy	Raw contrast <1e-9	Image-Plane and/or Pupil-Plane Coronagraph Designs	WFIRST/AFTA Coronagraph, ExEP studies, TPF	Unobscured Aperture, Contrast <1e-9	Developing	Highest
	Continuous speckle nulling WF control	WF sensing error <5 pm			<5 pm	Developing	Highest
	PSF Subtraction	10–30x contrast reduction	PSF matching, roll calibration, etc.	HST	100x contrast reduction on noisier images	Developing	Highest
Segmented mirror system	Mirror Segments	<20nm WFE; <5pm WFE drift/10 min	Improve production to reduce cost and lower mass; UV performance	Non-NASA MMSD; NASA AMSD, COR/AMTD, Industry R&D	ULE and SiC substrates to 1.4m size, <30 nm WFE, actuated	Substrate: TRL 4+; System: TRL 3	Highest
Ultra stability	Mirror Thermal Control	pm stability for coronagraph	Combining passive and active methods	Non-NASA; NASA various	nm stability	TRL 4	Highest
	Metrology (pm)	Picometer precision	Compact, lightweight laser truss metrology	SIM, Non-NASA	nm accuracy	TRL 3	High
Starshade	Advanced Starshade design	D ≥ 30m, Fr ≥ 12	Deployment; edge precision; long life	NASA EXEP; Industry R&D	D to 40 m	Developing	High
Sensitivity and Throughput	Ultra-low Noise and UV-sensitive Detectors	Detector noise & QE: Read: <0.1-1 e-; Dark <0.01 e-/s; QE(FUV): >50%	Exoplanet spectroscopic characterization and UV general astrophysics	NASA COR, commercial sources	Low noise, high QE photon-counting Vis-NIR and UV detectors	TRL 4-6	Highest

- HDST highest priority technologies address key performance issues, building on past and current NASA project and program investments

A Path Forward

- Most key HDST technologies are already being developed, under NASA COR and ExEP Programs, WFIRST/AFTA, JWST, and other sources
- Most of the highest HDST technical risks will be retired by successful completion of these projects, especially the WFIRST/AFTA Coronagraph – a technology precursor for HDST
- An HDST can be credibly proposed to the 2020 Decadal Survey for start in the mid to late 2020s, with some additional study, starting now
- These HDST-specific studies should build incrementally on current activities, to exploit the current rapid progress while keeping costs low

Specific Recommendations

- Design and analyze coronagraphs for a segmented, obscured HDST aperture, building on synergies with ExEP and AFTA Coronagraph
- Develop methods for ultra-stable telescopes for coronagraphy
  - Mirror and structure technologies for picometer stability and low cost, building on NASA/COR and non-NASA programs
  - System architectures for low vibration (non-contacting isolation, e.g.)
  - Methods for stability control, including continuous WF sensing, picometer metrology, DMs
- Continue development of ultra-low noise detectors in Vis/NIR
- Continue and expand exoEarth Yield studies, to include Starshade and mixed Coronagraph/Starshade architectures
  - Develop Starshade concepts compatible with 10-12 m class telescopes
  - Keep up with evolving scientific and technical understanding
- Explore on-orbit servicing in collaboration with NASA and other agencies
  - Far term: consider on-orbit assembly of Starshades or even telescopes

BACKUP

Starlight Suppression Status

Starlight Suppression Goals, Projections and Achievements to Date — 12/19/2014

	Method	Description	Pupil	Raw Contrast level	Detection Contrast (3-sigma)	IWA	OWA	Bandpass	Throughput	Telescope stability	Discussion
Full Scale	Science goal	With 10-12 m aperture		~1e-9	1.00E-10	<50 mas up to λ=1um	>1.5 asec				50 mas corresponds to Sun-Earth separation at 20 parsec
	Full-scale Coronagraph	Required performance for a 10 m aperture	Obscured, segmented	~1e-9	1.00E-10	<2.5 λ/D (<50 mas up to λ=1um)	>75 λ/D (>1.5 asec @ λ=1um)	10%	10-30%	Less than 10 pm wavefront change over the full observation	Challenges are (1) telescope stability, (2) throughput, (3) bandpass
	Full-scale Starshade	Required performance for an 10 m aperture, 80 m Star-shade, at 166 Mm distance, with Fresnel number Fr = 12	Any	~1e-9	1.00E-10	<50 mas up to λ=1um	Inf	λ≤1um	100%	10 nm / day	Challenges are (1) large size of starshade spacecraft, (2 retargeting time, (3) shape precision, (4) formation flying precision
Coronagraph Demos	Lyot coronagraph demonstration (2009)	Demonstrated on the subscale High Contrast Imaging Testbed (HCIT-1 or HCIT-2)	Unobscured, circular	5.00E-10		4 λ/D	10 λ/D	10%			Demonstration for TPF Milestone 2
	Hybrid Lyot coronagraph demonstration (2013)			1.20E-10		3.1 λ/D	15.6 λ/D	2%	56%		Current best demonstrated results
				3.20E-10				10%			
				1.30E-09				20%			
	Shaped-pupil coronagraph			1.20E-09		4.5 λ/D	13.8 λ/D	2%	10%		
				2.50E-09				10%			
	PIAA Coronagraph			5.70E-10		1.9 λ/D	4.7 λ/D	0%	46%		
				1.80E-08		2.2 λ/D	4.6 λ/D	10%			
	Vector vortex coronagraph (2013)			5.00E-10		3 λ/D	12 λ/D	0%	?		Unpublished results by Gene Serabyn.
				9.00E-09		2 λ/D	9 λ/D	10%			
	Visible Nuller Coronagraph (2012)	Demonstrated in ambient lab conditions at GSFC	Segmented pupil	5.68E-09		1.5 λ/D	2.5 λ/D	2%			6% bandpass to be demonstrated in early CY15.
	Shaped-pupil coronagraph	Demonstrated on HCIT	Obscured AFTA pupil	6.00E-09		4.5 λ/D	10 λ/D	2%	10%		First lab demo of high contrast with AFTA pupil
				9.00E-09				10%			
	Future Hybrid Lyot coronagraph demonstration (2015)	To be demonstrated on HCIT		<1e-9							Work in progress for AFTA
	Future PIAA coronagraph demonstration	To be demonstrated on HCIT		<5e-8		2 l/D			>50%		Work in progress for AFTA
Starshade Demos	Tabletop lab demo	Princeton, Fr = 620	Any	1.00E-10			800 mas	0%	100%	n/a	
	Desert demo	Demonstrated at km scale using artificial star Fr = 240		1.00E-08				60%			
	Large-scale shape TDEM-1	Full scale petal		n/a		n/a	n/a	n/a	n/a	n/a	Petal built to 1e-10 system contrast requirements.
	Large-scale deployment TDEM-2	2/3 scale truss		n/a		n/a	n/a	n/a	n/a	n/a	Truss with petals deployed to 1e-10 system contrast requirements.
	Future tabletop lab demo	Princeton, Fr = 12		3.00E-10		equiv 100 mas	TBD	>50%	100%	n/a	Approximately to scale, matching the target Fresnel number
	Future on-sky desert demo	Operating on a star, Fr = 50?									

Lower Priority, Architecture-Dependent Technologies

- Highest priority is given to technologies that are common to multiple potential architectures
- These lower-priority technologies include telescope architecture-dependent options, that would be best pursued under a pre-project architecture study

Technology Needed for Candidate Architectures				Current Status				
Technology Category	*Technology Provided*	*Performance Needed*	*Details*	*Heritage*	*Current Performance*	*Maturity*	*Priority*	*Scope*
Ultra Stability	Structural Thermal Control	pm stability for coronagraph, nm for starshade		Non-NASA; NASA various	um stability	TRL 3	High	Architecture
Ultra Stability	Non-contacting vibration isolation	140 dB isolation		Industry R&D	80 dB isolation	TRL 5	High	Architecture
Ultra Stability	Micro-thruster pointing control	Ultra-low vibration; uas pointing control	A possible option for low-disturbance LOS pointing, in lieu of RWs	Industry		TRL 3	High	Architecture
Monolithic Mirrors	4m Monolithic Mirrors	WFE < 20 nm; to 14" thick and 4m wide for f > 60 Hz	4 m monolith may provide a reduced-performance option	NASA COR/AMTD	to 14" thick and 30 cm wide	TRL 4	High	Architecture
Monolithic Mirrors	8m Monolithic Mirrors	WFE < 20 nm; to ~30" thick and 8m wide for f > 60 Hz	Launch requires development of SLS Block 2 10m fairing	NASA COR/AMTD	to 14" thick and 30 cm wide	TRL 3	Low	Architecture
Spacecraft	Deployment	2-fold, 6.5m aperture	S/C architecture dependent	JWST	2-fold, 6.5m aperture	TRL 6	Medium	Architecture
Spacecraft	Sunshade	T to ~90K, gimballed	S/C architecture dependent	JWST	T to 30K, fixed	TRL 6	Medium	Architecture
Wavefront Sensing & Control	WFS&C for initial alignment	<10 nm	Can use qualified methods	Non-NASA; NASA JWST	<10 nm	TRL 6	Low	Architecture

Lower Priority, Device Technologies

- These are higher-TRL devices and methods needed for any HDST

Technology Needed for Candidate Architectures				Current Status				
Technology Category	*Technology Provided*	*Performance Needed*	*Details*	*Heritage*	*Current Performance*	*Maturity*	*Priority*	*Scope*
Coronagraph	Segmented DMs for coronagraph WF control	Segmented to match PM, <10pm WFC	Needs control concept development	Industry R&D	Segmented facesheet, <100pm WFC	TRL 3	Medium	Device
Coronagraph	DMs for coronagraph WF control	<10pm WFC		NASA EXEP	Continuous facesheet, <100pm WFC	TRL 5	Low	Device
Segmented mirror system	RB Actuators	pm accuracy, 1 Hz operation, infinite life		Non-NASA; NASA JWST; Industry	cm stroke, nm accuracy	TRL 4-6	Medium	Device
Throughput	Coatings	Below 120 nm >50-70%, UV/Vis: >85-90%		NASA COR	High reflectance FUV Mirror Coatings	TRL 4-6	High	Device
Science data processing	PSF Subtraction	Additional 1e-1 contrast	Low cost	HST		Operational	High	Science

Starshade and Far-Term Technologies

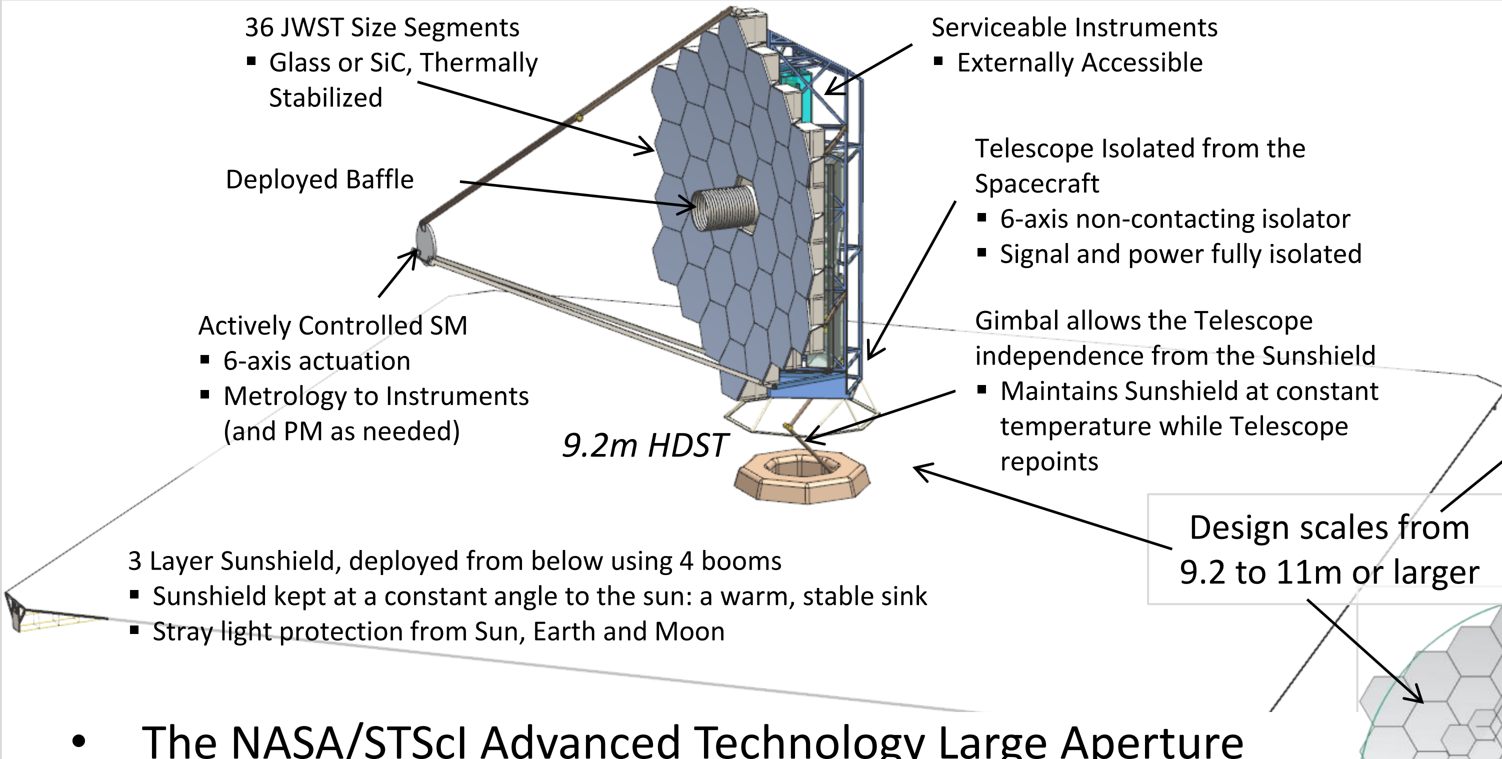
- Starshades provide an important alternative in case coronagraphs fall short, and a potentially useful complement for deeper characterization of identified exoEarths
- These starshade technologies are needed for scale-up to HDST-optimized capabilities

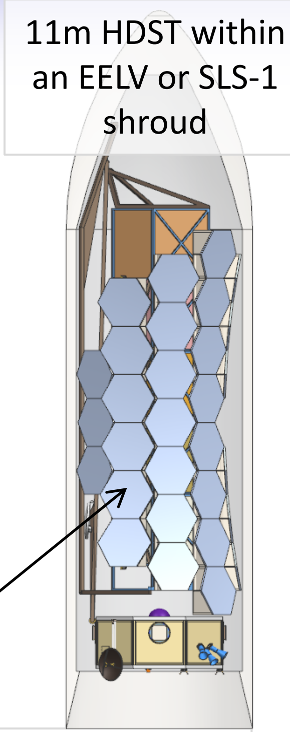
Technology Needed for Candidate Architectures				Current Status				
Technology Category	*Technology Provided*	*Performance Needed*	*Details*	*Heritage*	*Current Performance*	*Maturity*	*Priority*	*Scope*
Starshade	Starshade modeling and model validation	Validation at Fr = 12 or less	Full-scale starshades are not possible on the ground - need other methods to prove out	NASA EXEP	Models not yet validated at traceable Fresnel number	Developing	High	Starshade
Starshade	Starshade operations	Optimized for exoEarth yield and characterization	Operating strategies that minimize effects of retargeting	NASA EXEP	Days to weeks retargeting time	Developing	High	Starshade
Starshade	Starshade formation flying	Shadow control < 1 m over > 100,000 km sight lines	Includes metrology, propulsion, etc.	NASA EXEP		Developing	High	Starshade

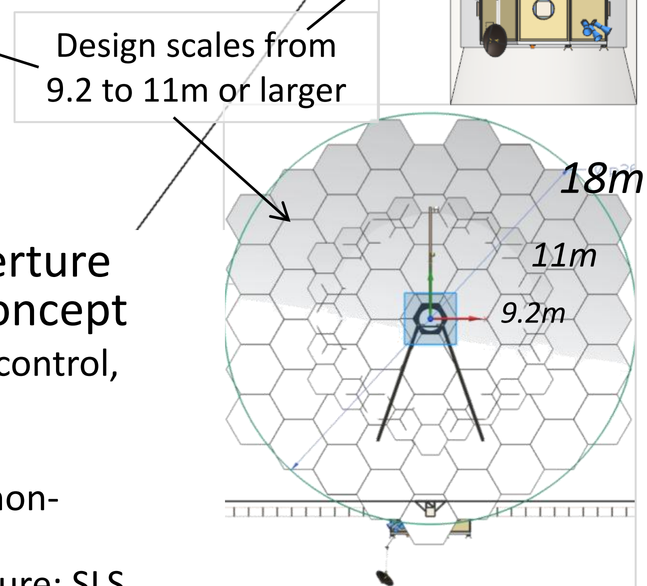
- Servicing has been vital for the Hubble Space Telescope performance and longevity

Technology Needed for Candidate Architectures				Current Status				
Technology Category	*Technology Provided*	*Performance Needed*	*Details*	*Heritage*	*Current Performance*	*Maturity*	*Priority*	*Scope*
Far term	Servicing	Robotic infrastructure required	High cost; high value; scope is multi-project	HST	Astronauts, Using STS	Mature, Abandoned	Low	Far term
Far term	On-orbit assembly of Starshade or Telescope	Robotic infrastructure required	Needed for largest structures; cost impact not known	NASA OPTIIX, DARPA, others		Early phase	Low	Far term

The NASA "ATLAST" Study







- The NASA/STScI Advanced Technology Large Aperture Space Telescope engineering reference design concept
  - JWST heritage: sunshield, deployment, passive thermal control, wavefront control, many lessons learned
  - NASA heritage: starlight suppression, metrology
  - Non-NASA heritage: light-weight non-cryogenic optics, non-contacting isolation, detectors and electronics
  - Launch vehicle: EELV-class or SLS Block 1 to ~12 m aperture; SLS Block 2 for larger apertures