Jet Propulsion Laboratory
California Institute of Technology

NASA Exoplanet Exploration Program

Dr. Gary Blackwood, Program Manager
Jet Propulsion Laboratory
California Institute of Technology

August 8, 2016

ART Meeting #2
Boulder, CO

Artist concept of Kepler-16b

Outline

- Program Overview
- Technology Investments: Coronagraphs
- Technology Investments: Starshade
- Preparing for Future Missions: Studies

Program Overview

NASA Exoplanet Exploration Program

Astrophysics Division, Science Mission Directorate

Purpose described in 2014 NASA Science Plan

1. Discover planets around other stars
2. Characterize their properties
3. Identify candidates that could harbor life

Exoplanet Exploration is both:

- *The Search for Life in our Galaxy*
- *All Planets Great and Small*

ExEP serves the science community and NASA by Implementing NASA's space science vision for exoplanets

http://exoplanets.nasa.gov

NASA Exoplanet Exploration Program

Astrophysics Division, Science Mission Directorate

Space Missions and Mission Studies

Kepler, K2 *WFIRST* *Starshade* *Decadal Studies* *Coronagraph*

Public Communications

Supporting Research & Technology

Key Sustaining Research

Large Binocular Telescope Interferometer

Keck Single Aperture Imaging and RV

NN-EXPLORE

Technology Development

Coronagraph Masks

High-Contrast Imaging

Deployable Starshades

NASA Exoplanet Science Institute

Archives, Tools, Sagan Fellowships, Professional Engagement

http://exoplanets.nasa.gov

NASA Exoplanet Exploration Program

Astrophysics Division, Science Mission Directorate

Program Office (JPL)

PM- Dr. G. Blackwood
DPM- K. Short
Chief Scientist – Dr. K. Stapelfeldt
Chief Technologist – Dr. N. Siegler

Program Science Office

PCS- Dr. K. Stapelfeldt
DPCS- Dr. E. Mamajek

Program Engineering Office

Chief Engineer
K. Warfield

Program Business Office

Mgr- R. Lemus

Mission Managers

Kepler – I. Heinrichsen
WFIRST – I. Heinrichsen

Business Operations

Resources – B. Nomoto
Schedule – G. Luzwick

Program Communications (JPL)

Mgr – M. Greene

Kepler (ARC)

PM – C. Sobeck
PS – Dr. N. Batalha
PS (K2) – Dr. J. Dotson

Program Technology (JPL)

Mgr– Dr. N. Siegler

LBTI

Mgr – Dr. P. Willems, JPL
PI – Dr. P. Hinz, UA

WFIRST Project Office (GSFC)

PM – K. Grady
DPM – C. Peddie
PS – Dr. N. Gehrels

Universe of Learning (JPL)

Mgr – M. Greene, Co-I

Starshade Technology Project (JPL)

Mgr – C. Henry (acting)

NN-EXPLORE

Mgr – Dr. P. Willems, JPL
PI - Dr. S. Mahadevan, PSU

NExScI (Caltech)

ED– Dr. C. Beichman
DD – Dr. R. Akeson
Mgr – Dr. D. Imel

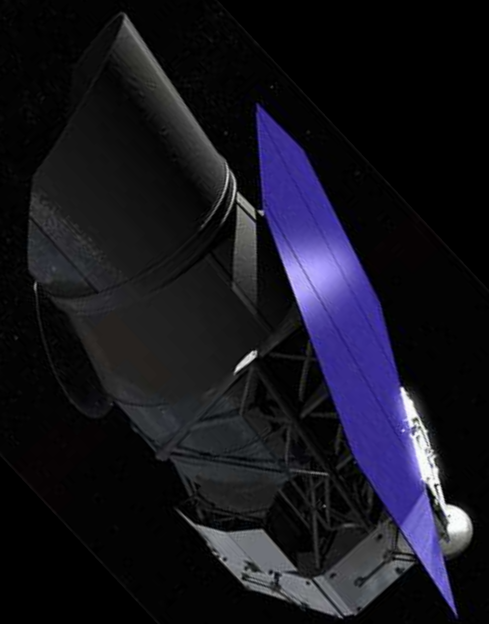
WFIRST Project Office (JPL)

PM - P. Barela
DPM – B. Parvin
PS - Dr W. Traub
DPS - Dr. J. Rhodes

WFIRST

Dark Energy, Alien Worlds

- WFIRST in Formulation Phase: NASA Key Decision Point (KDP)-A 2/17
- Formulation Science Working Group and Science Investigation Teams underway
- Wide Field Instrument Industry Concept Studies complete: Ball Aerospace and Lockheed Martin ATC
- Project received APD direction (June 2016) to incorporate starshade compatibility into Phase A DRM – for SMD decision following SRR/MDR



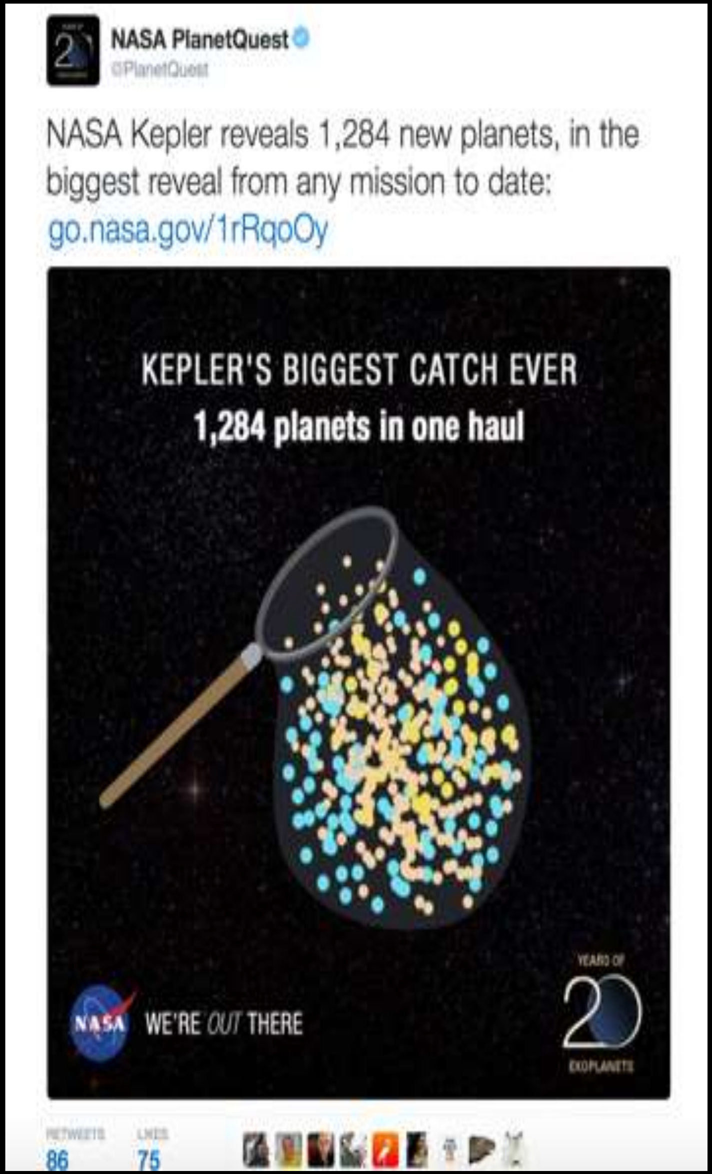
WFIRST Science

- Dark Energy Survey
- Widefield Infrared Survey
- Microlensing: Exoplanet Census
- Coronagraph Tech Demo: Exoplanet Direct Imaging

Kepler Close Out

Delivering Kepler's Legacy

- Kepler closeout and final data processing continues steadily on track
  - SOC 9.3 Q0-Q17 Short Cadence Light Curves Delivered to MAST
  - Documentation Completeness Review (Oct 2016)
  - SOC 9.3 Final Occurrence Rate Products (April 2017)



Kepler K2

Extending the Power of Kepler to the Ecliptic

- Data released through Campaign 8, Campaign 10 underway
  High-value exoplanets: small, rocky, nearby (46 pc), orbiting bright stars
- Spacecraft returned to science mode after loss of science module 4 (third of 21 detectors lost)
- K2 does much more than exoplanets - example: shock breakout seen in supernova lightcurve (Garnavich et al. 2016)

https://exoplanets.nasa.gov/k2/

Large Binocular Telescope Interferometer

Measures exozodiacal dust in habitable zones

Phil Hinz, PI
THE UNIVERSITY OF ARIZONA.

- Results of HOSTS survey to inform next decadal survey on direct exoplanet imaging
- Demonstrated 12-15 zodi sensitivity for a solar twin at 10 pc at May 2015,
- HOSTS survey interrupted by glycol leak in secondary mirror, repairs complete January 2016
- Plan to complete 35-star HOSTS survey by 2018 at 12 zodi or better

LBTI instrument (green structure) mounted between the two LBT primary mirrors

NN·EXPLORE

Partnership for Exoplanet Discovery and Characterization

- Motivation
  - 2010 Decadal Survey calls for precise ground-based spectrometer for exoplanet discovery and characterization
  - Follow-up & precursor science for current missions (K2, TESS, JWST, WFIRST)
- Scope:
  - Extreme precision radial velocity spectrometer (<0.5 m/s) for WIYN telescope
    - Penn State NEID proposal selected in March
    - Instrument to be commissioned by July 2019
  - Ongoing Guest Observer program using NOAO share of telescope time

NEID

NN-Explore Exoplanet Investigations with Doppler Spectroscopy

PennState

PI: S. Mahadevan

3.5m WIYN Telescope
Kitt Peak National Observatory
Arizona

Program Overview - Summary

Implementing Astro2010 Decadal Survey Priorities

- WFIRST: Astro2010 top priority

- Kepler => exoplanet occurrence rates

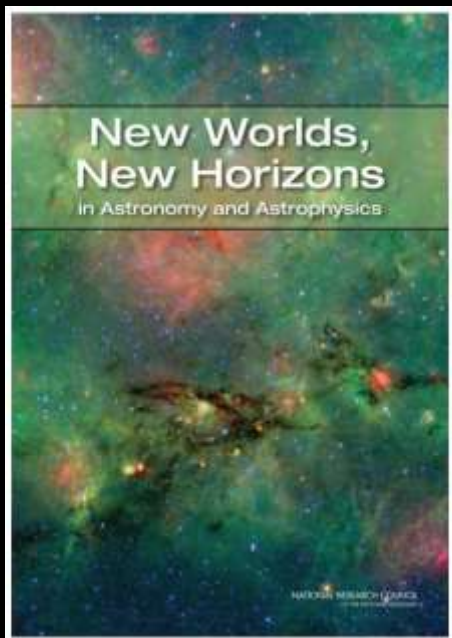
- LBTI => exozodiacal dust survey

- NNEXPLORE => radial velocity follow-up of TESS targets for JWST, precursor for WFIRST

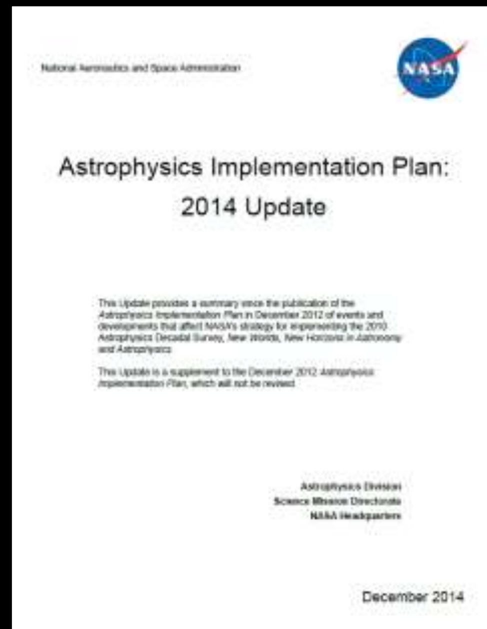
- Technology Investments for high contrast imaging

Technology Investments

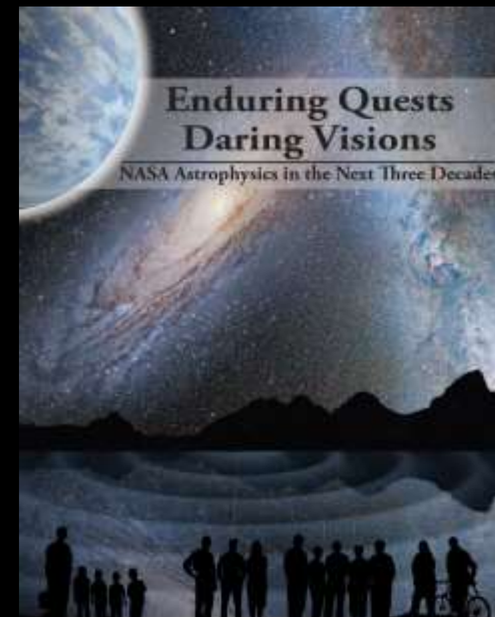
Driving Documents



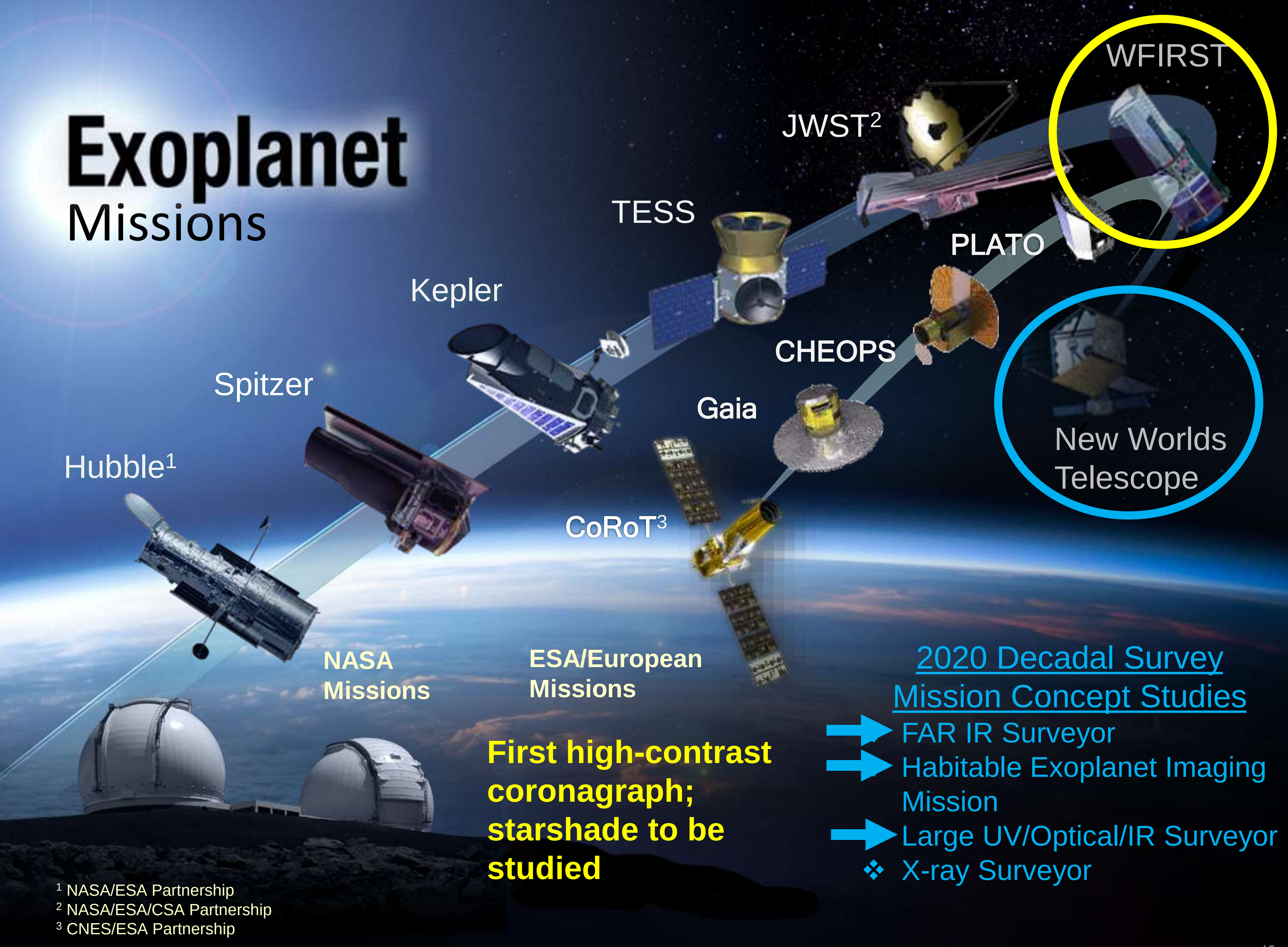
- **#1 large-scale recommendation: WFIRST**
- **#1 medium-scale recommendation:** Preparation for a planet imaging mission **(HabEx)**



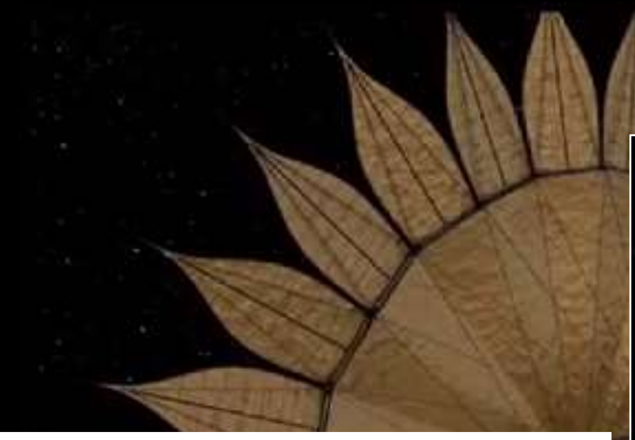
- **Confirms WFIRST as #1 Division priority after JWST**
- **Commissions Exo-C and Exo-S probe-class studies**

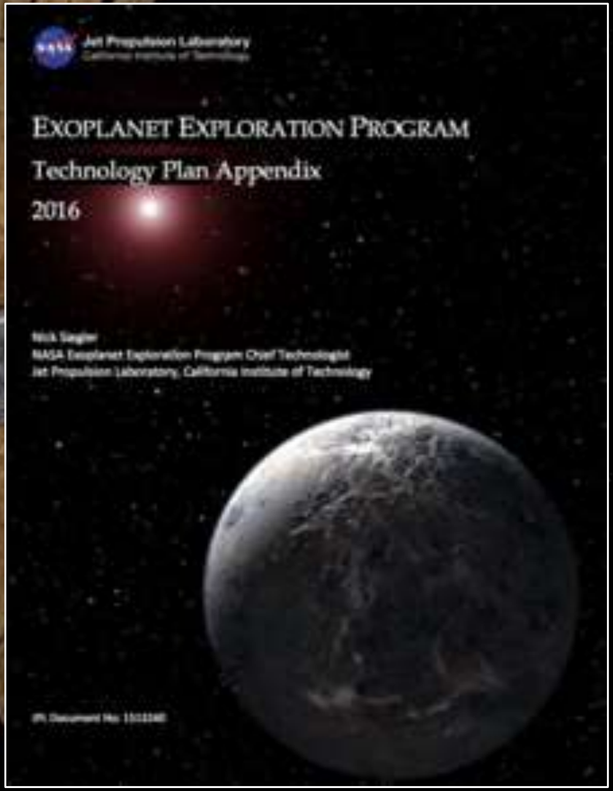


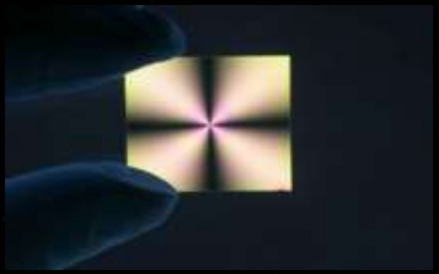
- **LUVOIR Surveyor**
- **Far-IR Surveyor**
- **X-Ray Surveyor**
- **Earth Mapper (interferometer)**


Exoplanet
Missions
Hubble[1]
Spitzer
Kepler
TESS
JWST[2]
WFIRST
PLATO
CHEOPS
Gaia
CoRoT[3]
New Worlds Telescope
NASA Missions
ESA/European Missions
First high-contrast coronagraph; starshade to be studied
2020 Decadal Survey Mission Concept Studies
FAR IR Surveyor
Habitable Exoplanet Imaging Mission
Large UV/Optical/IR Surveyor
X-ray Surveyor
[1] NASA/ESA Partnership
[2] NASA/ESA/CSA Partnership
[3] CNES/ESA Partnership

ExEP Technology Gap Lists







Starshade Technology Gap List

Table A.4 Starshade Technology Gap List

ID	Title	Description	Current	Required
S-1	Control Edge-Scattered Sunlight	Limit edge-scattered sunlight with optical petal edges that also handle stowed bending strain.	Graphite edges meet all specs except sharpness, with edge radius ≥10 μm.	Optical petal edges manufactured of high flexural strength material with edge radius ≤ 1 μm and reflectivity ≤ 10%.
S-2	Contrast Performance Demonstration and Optical Model Validation	Experimentally validate the equations that predict the contrasts achievable with a starshade.	Experiments have validated optical diffraction models at Fresnel number of ~500 to contrasts of 3×10^{-10} at 632 nm.	Experimentally validate models of starlight suppression to $\leq 3\times10^{-11}$ at Fresnel numbers ≤ 50 over 510-825 nm bandpass.
S-3	Lateral Formation Flying Sensing Accuracy	Demonstrate lateral formation flying sensing accuracy consistent with keeping telescope in starshade's dark shadow.	Centroid accuracy ≥ 1% is common. Simulations have shown that sensing and GN&C is tractable, though sensing demonstration of lateral control has not yet been performed.	Demonstrate sensing lateral errors ≤ 0.20m at scaled flight separations and estimated centroid positions ≤ 0.3% of optical resolution. Control algorithms demonstrated with lateral control errors ≤ 1m.
S-4	Flight-Like Petal Fabrication and Deployment	Demonstrate a high-fidelity, flight-like starshade petal and its unfurling mechanism.	Prototype petal that meets optical edge position tolerances has been demonstrated.	Demonstrate a fully integrated petal, including blankets, edges, and deployment control interfaces. Demonstrate a flight-like unfurling mechanism.
S-5	Inner Disk Deployment	Demonstrate that a starshade can be autonomously deployed to within the budgeted tolerances.	Demonstrated deployment tolerances with 12m heritage Astromesh antenna with four petals, no blankets, no outrigger struts, and no launch restraint.	Demonstrate deployment tolerances with flight-like, minimum half-scale inner disk, with simulated petals, blankets, and interfaces to launch restraint.

Coronagraph/Telescope Technology Gap List

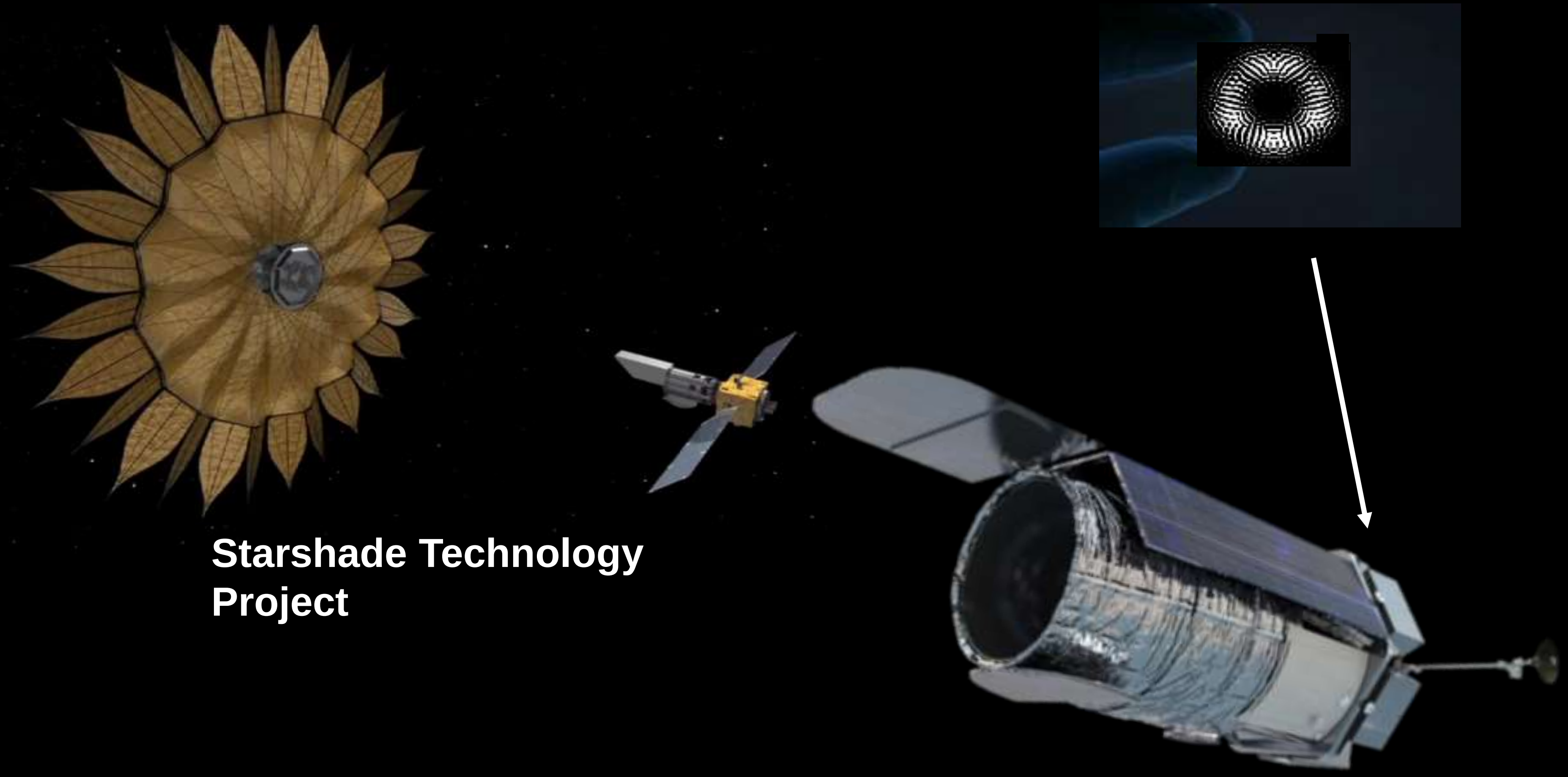
Table A.3 Coronagraph Technology Gap List

ID	Title	Description	Current	Required
C-1	Specialized Coronagraph Optics	Masks, apodizers, or beam-shaping optics to provide starlight suppression and planet detection capability.	A linear mask design has yielded 3.2×10^{-10} mean raw contrast from 3–16 λ/D with 10% bandwidth using an unobscured pupil in a static lab demonstration.	Circularly symmetric masks achieving $\leq 1\times10^{-10}$ contrast with IWA ≤ 3λ/D and ≥ 10% bandwidth on obscured or segmented pupils.
C-2*	Low-Order Wavefront Sensing & Control	Beam jitter and slowly varying large-scale (low-order) optical aberrations may obscure the detection of an exoplanet.	Tip/tilt errors have been sensed and corrected in a stable vacuum environment with a stability of 10^{-3} λ rms at sub-Hz frequencies.	Tip/tilt, focus, astigmatism, and coma sensed and corrected simultaneously to 10^{-4} λ (~10's of pm) rms to maintain raw contrasts of $\leq 1\times10^{-10}$ in a simulated dynamic testing environment.
C-3*	Large-Format Ultra-Low Noise Visible Detectors	Low-noise visible detectors for faint exoplanet characterization with an Integral Field Spectrograph.	Read noise of < 1 e⁻/pixel has been demonstrated with EMCCDs in a 1k × 1k format with standard read-out electronics.	Read noise < 0.1 e⁻/pixel in a ≥ 4k × 4k format validated for a space radiation environment and flight-accepted electronics.
C-4*	Large-Format Deformable Mirrors	Maturation of deformable mirror technology toward flight readiness.	Electrostrictive 64x64 DMs have been demonstrated to meet $\leq 10^{-9}$ contrasts in a vacuum environment and 10% bandwidth.	≥ 64x64 DMs with flight-like electronics capable of wavefront correction to $\leq 10^{-10}$ contrasts. Full environmental testing validation.
C-5	Efficient Contrast Convergence	Rate at which wavefront control methods achieve 10^{-10} contrast.	Model and measurement uncertainties limit wavefront control convergence and require many tens to hundreds of iterations to get to 10^{-10} contrast from an arbitrary initial wavefront.	Wavefront control methods that enable convergence to 10^{-10} contrast ratios in fewer iterations (10-20).
C-6*	Post-Data Processing	Techniques are needed to characterize exoplanet spectra from residual speckle noise for typical targets.	Few 100x speckle suppression has been achieved by HST and by ground-based AO telescopes in the NIR and in contrast regimes of 10^{-4} to 10^{-6}, dominated by phase errors.	A 10-fold improvement over the raw contrast of $\sim10^{-9}$ in the visible where amplitude errors are expected to no longer be negligible with respect to phase errors.

*Topic being addressed by directed-technology development for the WFIRST/AFTA coronagraph. Consequently, coronagraph technologies that will be substantially advanced under the WFIRST/AFTA technology development are not eligible for TDEMs.

http://exoplanets.nasa.gov/technology/

ExEP Technology Spinoffs



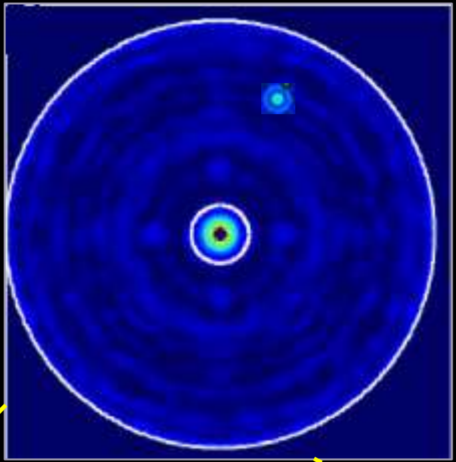
Starshade Technology Project

WFIRST Coronagraph Instrument

Technology Investments:

Coronagraphs

Coronagraph/Telescope Technology Gaps



Starlight Suppression

Coronagraph Architectures (CG-2)

Deformable mirrors (CG-3)

WFIRST

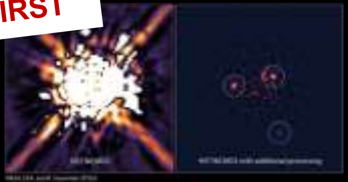


Image post-processing (CG-4)

Mirrors

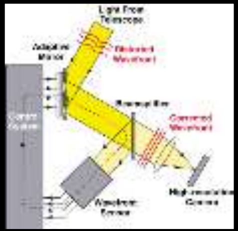
COR/PCOS

Systems and Design Reference Dependent

Large monolith (CG-1)

Segmented (CG-1)

WFE Stability



Wavefront sensing and control (CG-5)

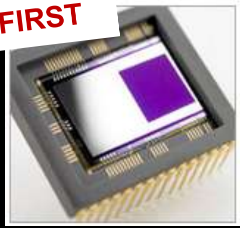
Systems and Design Reference Dependent

Segment phasing and rigid body sensing and control (CG-6)

Telescope vibration sensing and control (CG-7)

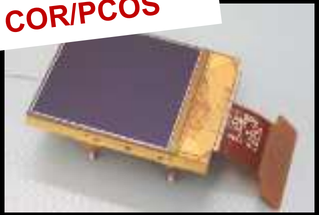
Detection Sensitivity

WFIRST



Ultra-low noise visible detectors (CG-8)

COR/PCOS



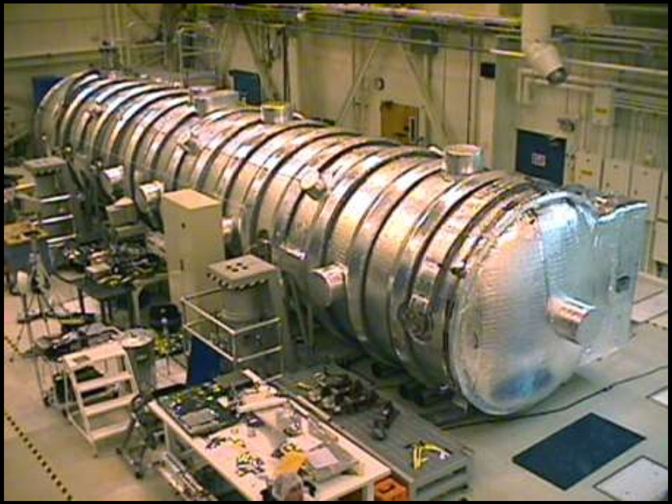
Ultra-low noise infrared detectors (CG-9)

High Contrast Imaging Testbeds (HCITs)

Test Facility

- Two vacuum chambers with 1 mTorr capability
- Seismically isolated, temperature-stabilized
- ~ 10 mK at RT.
- Narrow or broad band coronagraph system demos: Achieved 3×10^{-10} contrast (narrowband)
- Fiber/Pinhole “Star” Illumination
  - Monochromatic: 635, 785, 809, and 835 nm wavelengths
  - 2, 10, and 20% BW around 800 nm center
  - Medium and high power super-continuum sources
- CCD camera ($5e^-$), 13 μm pixels
- Complete computer control with data acquisition and storage
- Coronagraph model validation & error budget sensitivities. Remote access through FTP site.

HCIT-1
Single-testbed capacity (5’x8’)



HCIT-2
Two-testbed capacity (6’x10’)

Availability for two testbed in HCIT-2 expected beginning of CY17

Coronagraph Mask Technology

- TDEM investments (clear aperture)

Coronagraph	2009 SOA	2016 SOA
Hybrid Lyot	$6x10^{-10}$, monochromatic, 4-10l/D	$6x10^{-10}$, 10% BW, 4-10λ/D
PIAA	$2x10^{-7}$, monochromatic,1.65-4.4 l/D	5-$8x10^{-10}$, monochromatic, 2-4 λ/D
Vortex	$3.4x10^{-9}$, monochromatic, 2.5-12 l/D	$4.3x10^{-10}$, monochromatic,3-8 λ/D $3.2x10^{-8}$, 10% BW
Visible Nulling	$5x10^{-9}$,1.5% BW, 2-4 l/D	Same
Shaped Pupil	$2x10^{-9}$, 10% BW, 4-14λ/D	Same

- WFIRST Investments (on-axis obscured)
  - HLC: $8x10^{-9}$, 10% bandwidth, 3-9 λ/D, static
  - SPC: $8x10^{-9}$, 10% bandwidth, 3-9 λ/D, static
  - PIAA: in progress

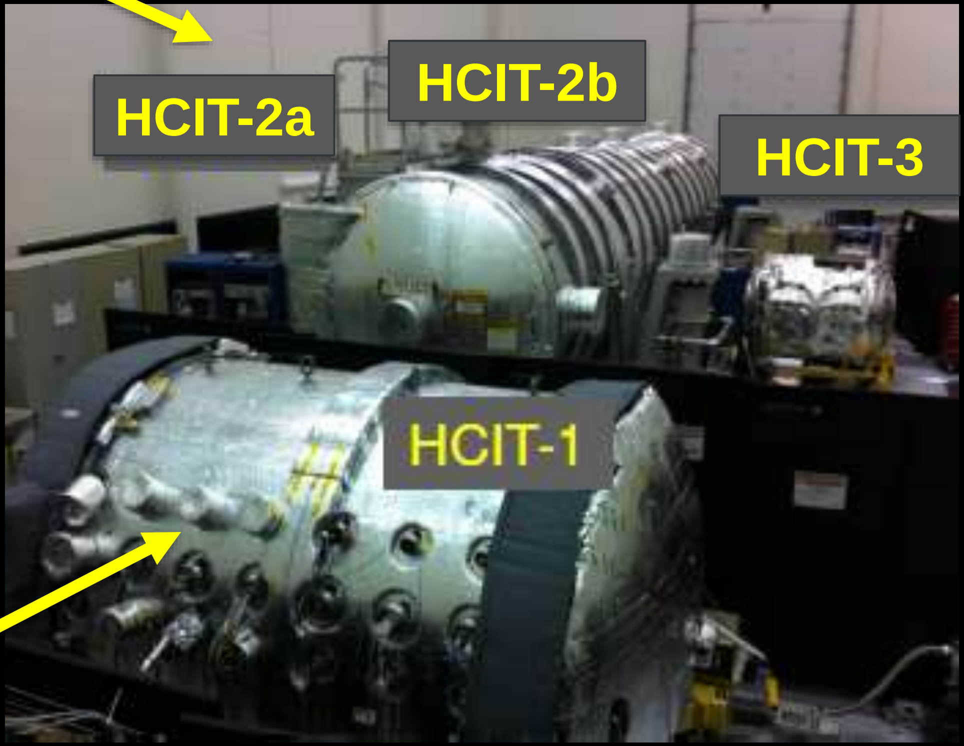
HCIT FY17 Coronagraph Facility Upgrades

Decadal Survey Testbed

In anticipation of future unobscured and segmented coronagraph demonstration needs, facility preparation for 10^{-10} contrast, 3 λ/D, and 10% broadband demo starting in FY17.

- Phase 1: proof-of-existence 10^{-10}
- Phase 2: static demo (unobscured or segmented)
- Phase 3: dynamic demo (unobscured or segmented)

WFIRST testbed



Technology Investments:

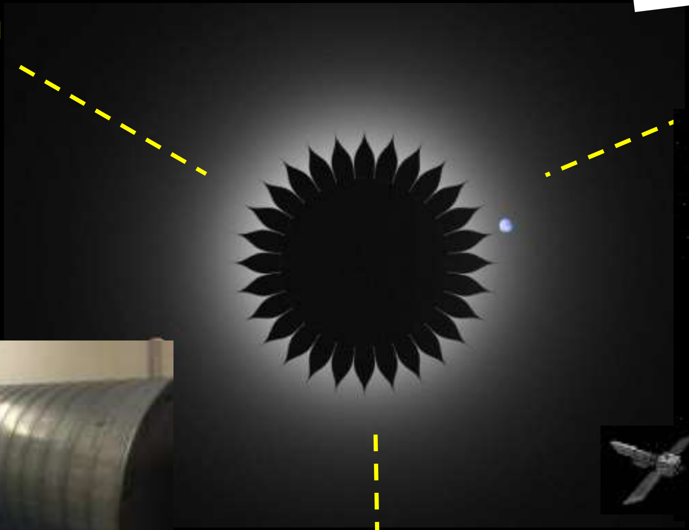
Starshades

Starshade Technology Gaps

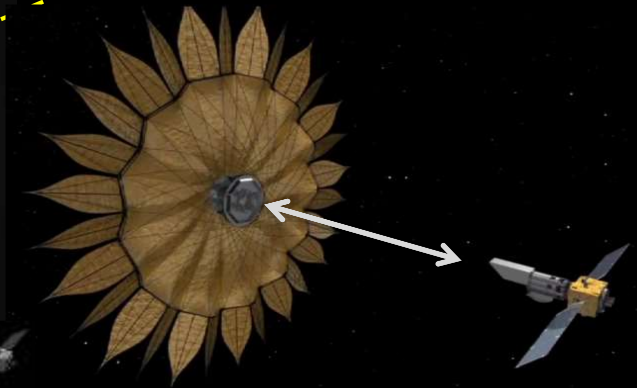
Starshade Technology Project

Starlight Suppression

Controlling Sunlight scattering off petal edges (S-2)



Formation Sensing and Control



Maintaining lateral offset requirement between the spacecrafts (S-3)

Suppressing starlight and validating optical model (S-1)

Deployment Accuracy and Shape Stability

Positioning the petals to high precision, blocking on-axis starlight, maintaining overall shape on a highly stable structure (S-5)

Fabricating the petal to high precision (S-4)

The Starshade Technology Project

- Purpose: achieve TRL5 by ~Decadal 2020
- Directed funding and reprogramming of competed funds
- March 23: APD Instructions to begin Planning Phase

Milestone	Description	Responsible Authority	Date
Design Review	Confirm updated reference mission is complete enough to begin tech development plan	Starshade Technology Project	May 2017
Technology Development Project Plan Review	Confirm technology development plan is complete and forms a good baseline to complete the planning of the implementation phase	Exoplanet Program Office	Jul 2017
Internal Planning Stage Review	Ensure Planning Stage Phase Plan is robust	JPL Director-for 7X	Aug 2017
Baseline TRL-5 Development Plan	Authorize start of Planning Stage Phase	SMD Astrophysics Division	Sep 2017

- Intent is broad institutional participation and funding
- Next step: Open workshop for work prioritization (Sept)

Starshade Laboratory

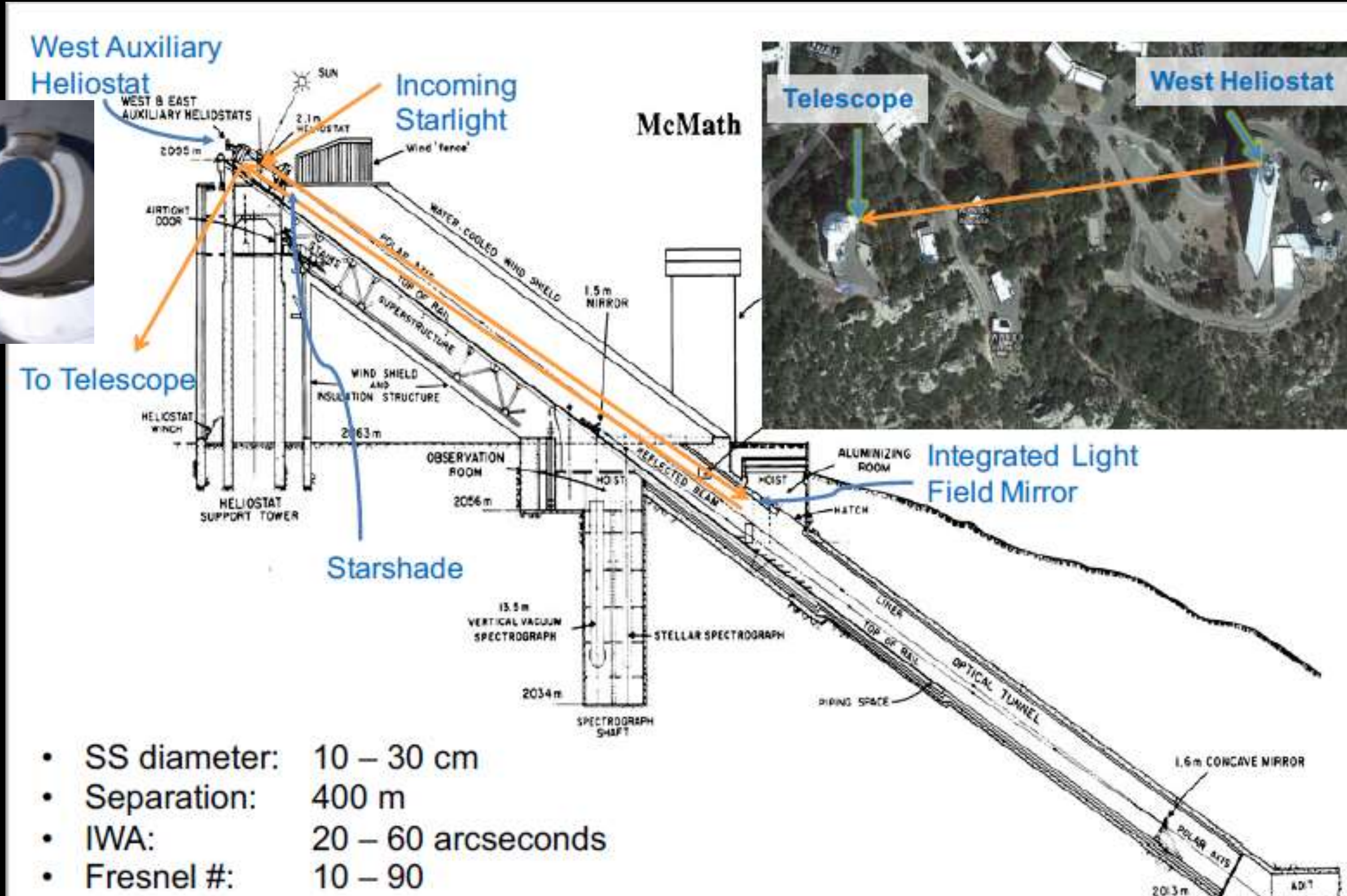
Jet Propulsion Laboratory

Starshade Laboratory

Jet Propulsion Laboratory

Starshade Field Tests: McMath Solar Telescope

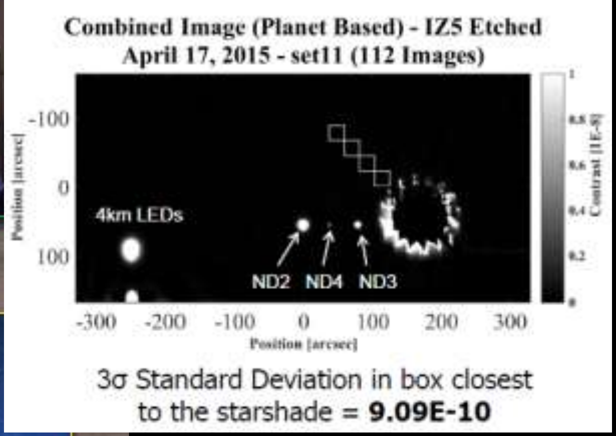
Northrop-Grumman, University of Colorado



- SS diameter: 10 – 30 cm
- Separation: 400 m
- IWA: 20 – 60 arcseconds
- Fresnel #: 10 – 90
- Telescope: 4 cm

Starshade Field Testing

1km testing for verification of models by JPL, NGAS, CU, PU



Preparing for Future Missions: Studies

Studies in Support of Exoplanet Direct Imaging

https://exoplanets.nasa.gov/exep/Studies/

Past Studies

- Many Coronagraphs; Starshades: New Worlds Observer, THEIA, O3

Recent Studies

- Probes:
  - Exo-C (Coronagraph)
  - Exo-S (Starshade, standalone and WFIRST Rendezvous)
- Probe Extended Studies:
  - Coronagraph
  - WFIRST Starshade Rendezvous

Current Studies

- Large Missions:
  - HabEx, LUVOIR, FarIR, XRay
- Starshade Readiness Working Group
- Segmented Coronagraph Design Analysis

Future

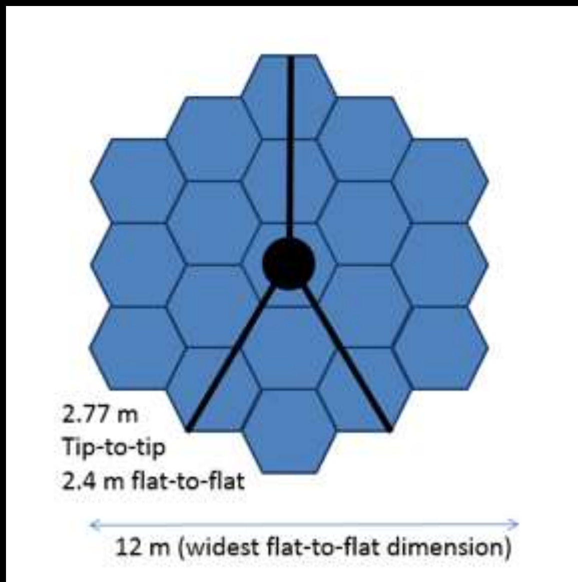
- Astrophysics Probes for Decadal Survey

Mission Studies

Starshade and Coronagraph

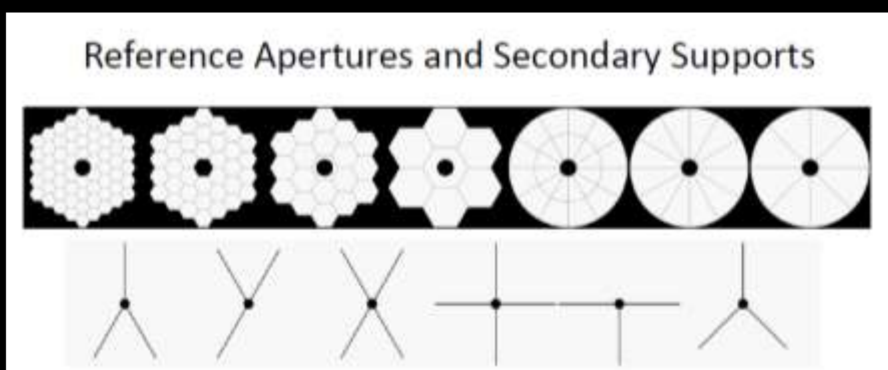
Study	Telescope Diameter (m)	Starshade Diameter (m)	Wavelength (nm)
NWO (2010)	4.0	50	250-1700
THEIA (2010)	4.0	40	250-1000
03 (2010)	1.1	40	250-1100
Exo-S Starshade Probe (2015)	1.1	30	400-1000
Exo-S Starshade Probe WFIRST Rendezvous(2015)	2.4	34	425-1000
Exo-S Extended Probe Study – WFIRST Rendezvous (2015)	2.4	20	425-1000
Study	**Telescope Diameter (m)**	**Telescope Design**	**Wavelength (nm)**
Exo-C Coronagraph Probe (2015)	1.4	Off-axis	450-1000
Exo-C Extended Probe Study (2016)	2.4	Off-axis	450-1000
WFIRST Coronagraph (Phase A)	2.4	On-axis	400-1000

Segmented Coronagraph Design Analysis



1. PIAA CMC (University of Arizona/NASA-Ames/JPL)
2. APLC/SPC (Space Telescope Science Institute/Princeton)
3. Vortex (Caltech/JPL)
4. Hybrid Lyot (Caltech/JPL)
5. Visible Nulling Coronagraph (NASA–GSFC)

<u>Recent Workshop (May 2016):</u>
https://exoplanets.nasa.gov/exep/events/160/



<u>Participants:</u>

- Stuart Shaklan (NASA-JPL) - Lead
- Lee Feinberg (NASA-GSFC)
- Phil Stahl (NASA-MSFC)
- Gary Matthews (Harris)
- Paul Lightsey (Ball)
- Scott Knight (Ball)
- Tony Hull (UNM)

Starshade Readiness Working Group

http://exoplanets.nasa.gov/sswg/

- Require a risk reduction plan for technology validation of starshades to enable starshade flight science missions to be considered in 2020 Decadal Survey
- Will answer these questions and deliver recommendation:
  - How to go from TRL 5 to ~TRL6,7
  - Do we need a tech demo, and if so, what is it?
- Adopted the Exo-S probe "Starshade Rendezvous" as representative motivation of technology requirements
- Chairs: G. Blackwood (ExEP/JPL), S. Seager (MIT)
- Status:
  - Consensus reached on musts, wants; options defined, technical and programmatic vetting underway
  - Kickoff: January 2016, Report to APD: October 2016.

Summary

Exoplanet Exploration Program

- Exoplanet Exploration Program implements the Astro2010 top priorities
  - – WFIRST, New Worlds Technology Program
  - – Kepler (occurrence rates) and LBTI (exozodi)
  - – NEID radial velocity facility instrument
- Technology Investments: Coronagraphs
- Technology Investments: Starshade
- Studies prepare for Future Missions

Jet Propulsion Laboratory
California Institute of Technology

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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- Work was also carried out at NASA
    - Goddard Space Flight Center
    - Ames Research Center

- Work was also carried out under contracts between the NASA and:
    - Princeton University
    - University of Arizona
    - Northrop Grumman Aerospace Systems
    - National Optical Astronomy Observatory
    - Massachusetts Institute of Technology
    - Pennsylvania State University
    - University of Colorado

Proposed 2017 Coronagraph Technology Gap List (1/2)

	ID	Title	Description	Current Capabilities	Needed Capabilities
Contrast	CG-2	Coronagraph Optics and Architecture	Coronagraph optics and architecture that suppress diffracted starlight by a factor of ≤ 10^{-9} at visible and infrared wavelengths.	$6x10^{-10}$ raw contrast at 10% bandwidth across angles of 3-16 λ/D demonstrated with a linear mask and an unobscured pupil in a static vac lab env't (Hybrid Lyot) < $8.8x10^{-9}$ raw contrast at 10% bandwidth across angles of 3-9 λ/D demonstrated with a circularly-symmetric mask and obscured pupil in a static vacuum lab	Coronagraph masks and optics capable of creating circularly symmetric dark regions in the focal plane enabling raw contrasts ≤ 10^{-9}, IWA ≤ 3 λ/D, throughput ≥ 10%, and bandwidth ≥ 10% on obscured/segmented pupils in a simulated dynamic vacuum lab environment.
Angular Resolution (plus sensitivity, integration time, and planet yield)	CG-1	Large Aperture Primary Mirrors	Large monolith and multi-segmented mirrors that meet tight surface figure error and thermal control requirements at visible wavelengths.	Monolith: 3.5m sintered SiC with < 3 um SFE (Herschel) 2.4m ULE with ~ 10 nm SFE (HST) Depth: Waterjet cutting is TRL 9 to 14", but TRL 3 to >18". Fused core is TRL 3; slumped fused core is TRL 1. Segmented: 6.5m Be with 25 nm SFE (JWST) Non-NASA: 6 dof, 1-m class SiC and ULE, < 20 nm SFE, and < 5 nm wavefront stability over 4 hr with thermal control	Aperture: 4m - 12m; SFE < 10 nm rms (wavelength coverage 400 nm - 2500 nm) Wavefront stability better than 10 pm rms per wavefront control time step. Segmented apertures leverage 6 DOF or higher control authority meter-class segments for wavefront control. Environmentally tested.
Detection Sensitivity	CG-8	Ultra-Low Noise, Large Format Visible Detectors	Low-noise visible detectors for faint exoplanet characterization with an Integral Field Spectrograph	1kx1k silicon EMCCD detectors provide dark current of $8x10^{-4}$ e-/px/sec; effective read noise < 0.2 e- rms (in EM mode) after irradiation when cooled to 165.15K (WFIRST). 4kx4k EMCCD fabricated but still under development.	Effective read noise < 0.1e- rms; CIC < $3x10^{-3}$ e-/px/fram; dark current < 10^{-4} e-/px/sec tolerant to a space radiation environment over mission lifetime. ≥ 2kx2k format
Detection Sensitivity	CG-9	Ultra-Low Noise, Large Format Near Infrared Detectors	Near infrared wavelength (900 nm to 2.5 μm), extremely low noise detectors for exo-earth spectral characterization with Integral Field Spectrographs.	HgCdTe photodiode arrays have read noise <~ 2 e- rms with multiple non-destructive reads; dark current < 0.001 e-/s/pix; very radiation tolerant (JWST). HgCdTe APDs have dark current ~ 10-20 e-/s/pix, RN << 1 e- rms, and < 1kx1k format Cryogenic (superconducting) detectors have essentially no read noise nor dark current; radiation tolerance is unknown.	Read noise << 1 e- rms, dark current < 0.001 e-/pix/s, in a space radiation environment over mission lifetime. ≥ 2kx2k format

Proposed 2017 Coronagraph Technology Gap List (2/2)

Exoplanet Exploration Program

	ID	Title	Description	Current Capabilities	Needed Capabilities
Contrast Stability	CG-6	Segment Phasing Sensing and Control	Multi-segment large aperture mirrors require phasing and rigid-body sensing and control of the segments to achieve tight static and dynamic wavefront errors.	6 nm rms rigid body positioning error and 49 nm rms stability (JWST error budget) SIM and non-NASA: nm accuracy and stability using laser metrology	Systems-level considerations to be evaluated but expect will require less than 10 pm rms accuracy and stability.
Contrast Stability	CG-7	Telescope Vibration Control	Isolation and damping of spacecraft and payload vibrational disturbances	80 dB attenuation at frequencies > 40 Hz (JWST passive isolation) Disturbance Free Payload demonstrated at TRL 5 with 70 dB attenuation at "high frequencies" with 6-DOF low-order active pointing.	Monolith: 120 dB end-to-end attenuation at frequencies > 20 Hz. Segmented: 140 dB end-to-end attenuation at frequencies > 40 Hz. End-to-end implies isolation between disturbance source and the telescope.
Contrast	CG-3	Deformable Mirrors	Environment-tested, flight-qualified large format deformable mirrors	Electrostrictive 64x64 DMs have been demonstrated to meet $\leq 10^{-9}$ contrasts and $< 10^{-10}$ stability in a vacuum environment and 10% bandwidth; 48x48 DM passed random vibe testing.	4 m primary: ≥ 96x96 actuators 10 m primary: ≥ 128x128 actuators Enable raw contrasts of $\leq 10^{-9}$ at ~20% bandwidth and IWA $\leq 3\ \lambda/D$ Flight-qualified device and drive electronics (radiation hardened,environmentally tested, life-cycled including connectors and cables) Large segment DM needs possible for segmented telescopes.
Contrast Stability	CG-5	Low-Order Wavefront Sensing and Control	Sensing and control of line of sight jitter and low-order wavefront drift	< 0.5 mas rms per axis LOS residual error demonstrated in lab with a fast-steering mirror attenuating a 14 mas LOS jitter and reaction wheel inputs; ~ 100 pm rms sensitivity of focus (WFIRST). Higher low-order modes sensed to 10-100 nm WFE rms on ground-based telescopes.	Sufficient fast line of sight jitter (< 0.5 mas rms residual) and slow thermally-induced (≤ 10 pm rms sensitivity) WFE sensing and control to maintain closed-loop $< 10^{-9}$ raw contrast with an obscured/segmented pupil and simulated dynamic environment.
Contrast	CG-4	Post-Data Processing	Post-data processing techniques to uncover faint exoplanet signals from residual speckle noise at the focal-plane detector.	Few 100x speckle suppression has been achieved by HST and by ground-based AO telescopes in the NIR and in contrast regimes of 10^{-4} to 10^{-5}, dominated by phase errors.	A 10-fold contrast improvement in the visible from 10^{-9} raw contrast where amplitude errors are expected to be important (or a demonstration of the fundamental limits of post-processing)

Proposed 2017 Starshade Technology Gap List

Proposed 2017 Starshade Technology Gap List

	ID	Title	Description	Current Capabilities	Needed Capabilities
Optical Performance and Model Validation	S-2	Optical Performance Demonstration and Validated Optical Model	Experimentally validate the equations that predict the contrasts achievable with a starshade.	3×10^{-10} contrast at 632 nm, 5 cm mask, and ~500 Fresnel #; validated optical model 9×10^{-10} contrast at white light, 58 cm mask, and 210 Fresnel #	Experimentally validate models predicting contrast to ≤ 10^{-10} just outside petal edges in scaled flight-like geometry with Fresnel numbers ≤20 across a broadband optical bandpass.
	S-1	Controlling Scattered Sun Light	Limit edge-scattered sunlight and diffracted starlight with optical petal edges that also handle stowed bending strain.	Machined graphite edges meet all specs but edge radius (10 um); etched metal edges meet all specs but in-plane shape tolerance (Exo-S design).	Integrated petal optical edges maintaining precision in-plane shape requirements after deployment trials and limiting contrast contribution of solar glint to < 10^{-10} at petal edges.
Formation Sensing and Control	S-3	Lateral Formation Sensing	Demonstrate lateral formation flying sensing accuracy consistent with keeping telescope in starshade's dark shadow.	Centroid star positions to ≤ 1/100th pixel with ample flux. Simulations have shown that sensing and GN&C is tractable, though sensing demonstration of lateral control has not yet been performed.	Demonstrate sensing lateral errors ≤ 0.30 m accuracy at scaled flight separations (±1 mas bearing angle). Estimated centroid positions to ≤ 1/40th pixel with limited flux from out of band starlight. Control algorithms demonstrated with scaled lateral control errors corresponding to ≤ 1 m.
Deployment Accuracy and Shape Stability	S-5	Petal Positioning Accuracy and Opaque Structure	Demonstrate that a starshade can be autonomously deployed to within its budgeted tolerances after exposure to relevant environments.	Petal deployment tolerance (≤ 1 mm) verified with low fidelity 12m prototype and no optical shield; no environmental testing (Exo-S design).	Deployment tolerances demonstrated to ≤ 1 mm (in-plane envelope) with flight-like, minimum half-scale structure, simulated petals, opaque structure, and interfaces to launch restraint after exposure to relevant environments.
	S-4	Petal Shape and Stability	Demonstrate a high-fidelity, flight-like starshade petal meets petal shape tolerances after exposure to relevant environments.	Manufacturing tolerance (≤ 100 μm) verified with low fidelity 6m prototype and no environmental tests. Petal deployment tests conducted but on prototype petals to demonstrate rib actuation; no shape measurements.	Deployment tolerances demonstrated to ≤ 100 μm (in-plane envelope) with flight-like, minimum half-scale petal fabricated and maintains shape after multiple deployments from stowed configuration.

Strategic Astrophysics Technology - TDEM

Reports for completed and active TDEMs: http://exep.jpl.nasa.gov/technology/
Reviewed and approved by ExoTAC, Alan Boss (chair)

- Active TDEMs
  - 2010
    - (Bierden) Environmental Testing of MEMs DMs
    - (Helmbrecht) Environmental Testing of MEMs DMs
  - 2012
    - (Kasdin) Optical and Mechanical Verification of External Occulter
  - 2013
    - (Bendek) Enhanced Direct Imaging with Astrometric Mass
    - (Cash) Development of Formation Flying Sensors
  - 2014
    - (Bolcar) Next Generation Visible Nulling
    - (Serabyn) Broadband Vector Vortex Coronagraph

WFIRST Technology Milestones

MS #	Milestone	Date
1	First-generation reflective Shaped Pupil apodizing mask has been fabricated with black silicon specular reflectivity of less than 10^{-4} and 20 µm pixel size.	7/21/14
2	Shaped Pupil Coronagraph in the High Contrast Imaging Testbed demonstrates 10^{-8} raw contrast with narrowband light at 550 nm in a static environment.	9/30/14
3	First-generation PIAACMC focal plane phase mask with at least 12 concentric rings has been fabricated and characterized; results are consistent with model predictions of 10^{-8} raw contrast with 10% broadband light centered at 550 nm.	12/15/14
4	Hybrid Lyot Coronagraph in the High Contrast Imaging Testbed demonstrates 10^{-8} raw contrast with narrowband light at 550 nm in a static environment.	2/28/15
5	Occulting Mask Coronagraph in the High Contrast Imaging Testbed demonstrates 10^{-8} raw contrast with 10% broadband light centered at 550 nm in a static environment.	9/15/15
6	Low Order Wavefront Sensing and Control subsystem provides pointing jitter sensing better than 0.4 mas and meets pointing and low order wavefront drift control requirements.	9/30/15
7	Spectrograph detector and read-out electronics are demonstrated to have dark current less than 0.001 e/pix/s and read noise less than 1 e/pix/frame.	8/25/16
8	PIAACMC coronagraph in the High Contrast Imaging Testbed demonstrates 10^{-8} raw contrast with 10% broadband light centered at 550 nm in a static environment; contrast sensitivity to pointing and focus is characterized.	9/30/16
9	Occulting Mask Coronagraph in the High Contrast Imaging Testbed demonstrates 10^{-8} raw contrast with 10% broadband light centered at 550 nm in a simulated dynamic environment.	9/30/16

Technology - Coronagraph

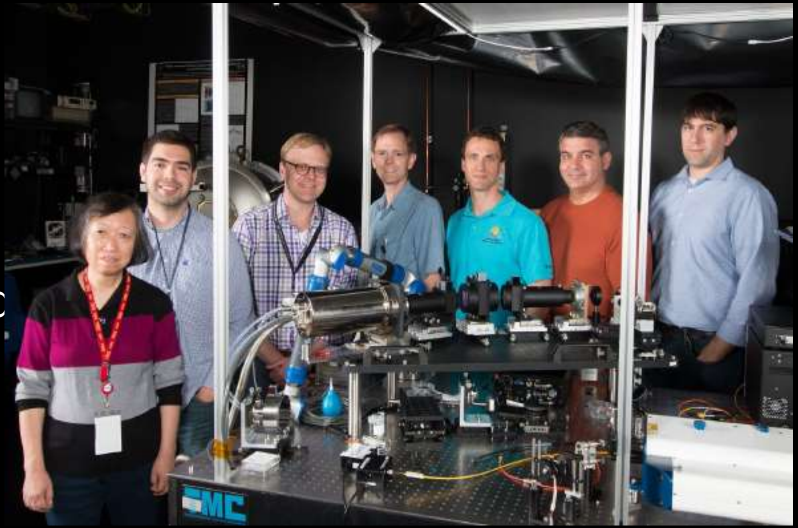
All prior WFIRST technology milestones met on schedule

PISCES Integral Field Spectrograph hardware delivered by GSFC to HCIT

- First demonstration of ultra-high contrast spectroscopy for characterization of exoplanets and image speckles
- Setup and initial testing this summer
- New PI Avi Mandell

Key upcoming milestones by 9/30/16:

- Read noise of EMCCD detector+readout
- First lab demo of PIAACMC coronagraph
- Demonstrate 10^{-8} raw contrast in 10% band in a simulated dynamic environment



Exo-S Extended Probe Study completed

(Seager et al.)

- Options for follow-on missions with WFIRST, with operations at the Earth-Sun L2 point.
- Petal optimization for detection in blue band could improve Tech Demo and Extended Study IWA

Mission Option Characteristics							Performance Characteristics				
Option	Starshade Size	Mission Duration	Mission Class	Launch Option	Retarget Propulsion	Ball-Park Mission Cost	Search Mode IWA	Search Mode Bandpass	Telescope Separation	Exo-Earth Detections*	Exo-Earth Character-izations
Exo-S Tech Demo	20 m	1 yr.	D	Antares 3m fairing	Monoprop	$300M	100 mas	425-565 nm	20 Mm	≥1 candidate	0
Exo-S Extended Study	20 m	3 yr.	C	Falcon 9 5m fairing	Biprop	$450M	100 mas	425-565 nm	20 Mm	≥1	<1
Exo-S Case Study	34 m	3 yr.	C	Falcon-9 5m fairing	Biprop	$600M	70 mas	425-602 nm	50 Mm	≥2	≥1
Exo-S Enhanced	40 m	5 yr.	B	Falcon-9 5m fairing	SEP	$900M	50 mas	425-560 nm	82 Mm	≥4	≥2

Version	Parameters	Observing Bands		
		Blue	Green	Red
Case Study	Bandpass (nm)	425-602	600-850	706-1000
20m inner disk	IWA (mas)	70	100	118
28 7m petals	Separation (Mm)	50	35	30
Extended study	Bandpass (nm)	425-565	600-800	750-1000
10m inner disk	IWA (mas)	100	140	176
28 5m petals	Separation (Mm)	20.5	15	12

Exo-S ES compared to Exo-S CS

- **Discovery:** Stars that could be searched have the same quality images as before. Fewer targets with desirable IWA
- **Characterization by spectra:** only blue band is accessible for exoEarths
- **Background discrimination:** lack of colors at small IWA hurts for background contamination

Exo-C Extended Probe Study Completed
(Cahoy et al.)

- Exo-C ES report captures the science capability of a 2.4-m aperture space telescope designed specifically for exoplanet direct imaging.
- Highlights technology development needs beyond WFIRST:
  - 4k x 4k radiation-tolerant EMCCD detectors
  - 96 x 96 actuator deformable mirrors
  - Refinement and validation of contrast stability models to 10^{-11}
- Considered possible secondary payloads.
  - NIR coronagraph, Transit Spectrometer, NIRSpec “Lite”