Exoplanet Technology Gaps

Nick Siegler

Chief Technologist

Brendan Crill

Deputy Chief Technologist

Exoplanet Exploration Program (ExEP)

Jet Propulsion Laboratory / California Institute of Technology

Space Studies Board Committee of Exoplanet Science Strategy

20 April 2018

The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

Pre-Decisional Information -- For Planning and Discussion Purposes Only

Copyright 2018 California Institute of Technology. U.S. Government sponsorship acknowledged.

The 2010 Decadal Survey and its Effect on Exoplanet Technology Priorities

ExEP's Technology Focus

The ExEP technology focus is to enable the ExEP science goals:

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

ExEP's Technology Priorities

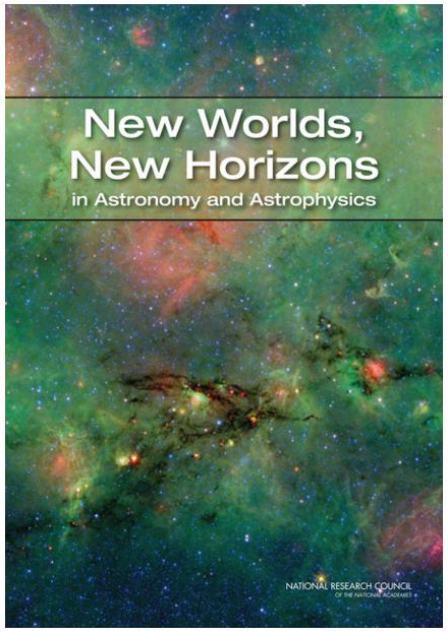


TABLE ES.4 Space: Recommended Activities—Medium-Scale (Priority Order)

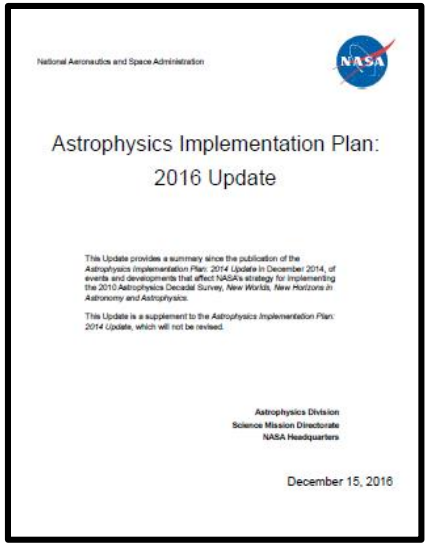
Recommendation	Science	Appraisal of Costs[a]
1. New Worlds Technology Development Program	Preparation for a planet-imaging mission beyond 2020, including precursor science activities	$100M to $200M
2. Inflation Probe Technology Development Program	Cosmic microwave background (CMB)/ inflation technology development and preparation for a possible mission beyond 2020	$60M to $200M

"…high-priority science areas for which mid-term investments are needed beginning early in the decade, including development of a variety of technologies for exoplanet imaging, such as coronagraphs, interferometers, and starshades, leading to possible late-decade down-selecting."

APD Response to the 2010 Decadal Survey Recommendations

Decadal Survey Recommendation	NASA Actions
Large-scale 1. WFIRST	In Phase A, launch in mid-2020s (see Section 4)
Large-Scale 2. Augmentation to Explorer Program	Executing 4 Announcements of Opportunity (AOs) per decade (see Section 5)
Large-Scale 3. LISA	Partnering on ESA's space-based gravitational wave observatory (see Section 6.1)
Large-Scale 4. IXO	Partnering on ESA's Athena X-ray observatory (see Section 6.2)
Medium-Scale 1. New Worlds Technology Development Program	WFIRST coronagraph; starshade and coronagraph technology development; Doppler spectrograph on WIYN telescope; exozodiacal dust survey with LBTI (see Section 7.1)
Medium-Scale 2. Inflation Probe Technology Development Program	Multiple balloon-borne investigations plus SAT investments (see Section 7.2)
Small-Scale. Research Program Augmentations	R&A as of FY2016 up 20% from FY2010; increase not targeted except TCAN (see Section 7.3)
Small-Scale. Intermediate Technology Development Augmentation	Initiated Strategic Astrophysics Technology program; focused on identified strategic missions
Small-Scale. SPICA (U.S. contribution)	Not supported as a strategic contribution; candidate for Explorer Mission of Opportunity

Table 1. Recommended space activities of the 2010 Decadal Survey supported by the FY 2016 NASA Appropriation, the FY 2017 President's Budget Request, and its notional out year planning budget.



National Aeronautics and Space Administration

Astrophysics Implementation Plan: 2016 Update

This Update provides a summary since the publication of the *Astrophysics Implementation Plan: 2014 Update* in December 2014, of events and developments that affect NASA's strategy for implementing the 2010 Astrophysics Decadal Survey, *New Worlds, New Horizons in Astronomy and Astrophysics*.

This Update is a supplement to the *Astrophysics Implementation Plan: 2014 Update*, which will not be revised.

Astrophysics Division
Science Mission Directorate
NASA Headquarters

December 15, 2016

APD Implementation Plan (2016)

APD = Astrophysics Division (NASA)

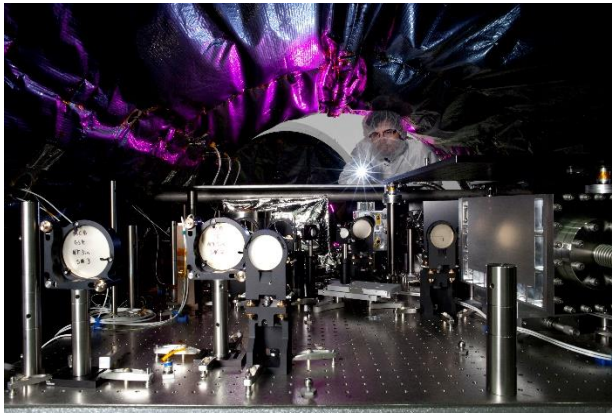
New Worlds Technology Development
(Medium Scale Recommendation #1)

- **Decadal Survey Recommendation:**
  - *"Candidate starlight suppression techniques be developed to a level such that mission definition for a space-based planet imaging and spectroscopy mission could start late in the decade."*

- **APD Response:**
  - Continued use of competitively selected individual investigator awards issued under the Astrophysics Research and Analysis (APRA) and Strategic Astrophysics Technology (SAT) programs.
  - APRA addresses early-TRL technologies (1-2)
  - SAT addresses mid-TRL technologies (3-5)
    - Within the SAT, Technology Development for Exoplanet Missions (TDEM) primarily focuses on exoplanet technologies.

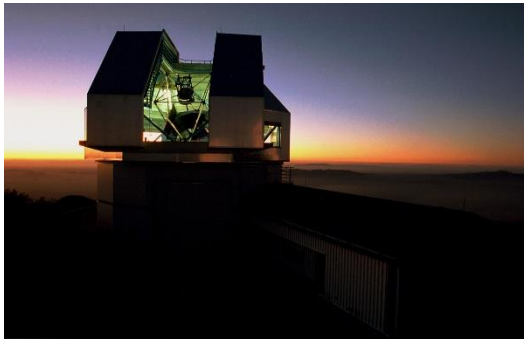
Exoplanet Technology Activities

- More than 37 awards have advanced the technology readiness of starshades, coronagraphs, and their associated supporting technologies.
- In 2013, coronagraphy was “spun off” from the ExEP to the WFIRST project to support technology advancement for their coronagraph instrument.
  - Though ExEP continues to advance coronagraphy beyond WFIRST’s performance level.
- In 2016, the starshade was spun off to establish a starshade technology development activity with the goal of advancing starshade technology to TRL 5.

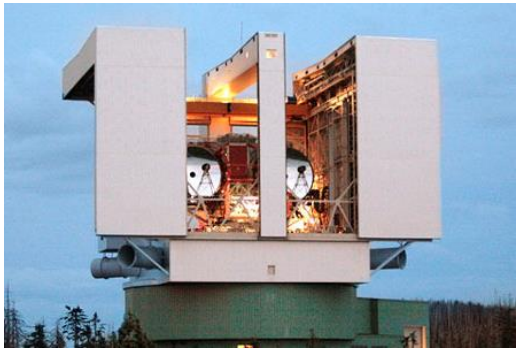


Additional Technology Activities in Support of 2010 Decadal Recommendations

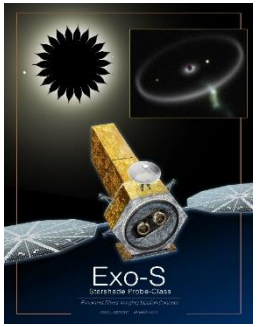
- NASA is developing an Extreme Precision Doppler Spectrometer (EPDS) to be installed as a facility-class instrument on the WIYN telescope; the EPDS instrument is scheduled for commissioning in 2019.

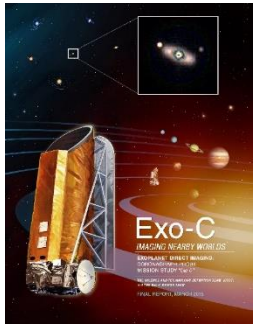


- NASA invested in the LBTI and the associated survey of exozodiacal dust levels around a set of nearby stars reached its target of 35 stars in 2018.



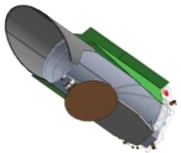
- APD chartered the Exo-C and Exo-S studies to study the feasibility of possible medium-size missions (total mission cost less than $1B) for direct imaging of exoplanets.





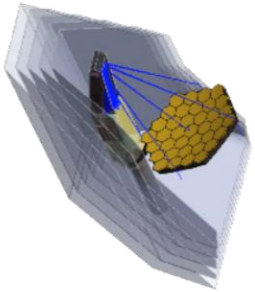
Exoplanet Technology Initiatives for the Next Decadal

- APD chartered four large space mission concepts to develop design reference missions to be submitted as inputs into the 2020 Decadal.
- APD later selected 12 medium-sized concepts through an open solicitation process for study by science teams.
- Of the four large mission concepts, three have exoplanet science as important science goals; of the twelve medium-sized concepts, two have exoplanet science as important science goals (space RV instrument and a Starshade Rendezvous).



HabEx

LUVOIR



OST

Midterm Assessment

NASA Activity	Midterm Assessment Finding	NASA Response
New Worlds Technology Development	Finding 4-11: The current planned decadal investment in NWNH-recommended technology development and precursor science exceeds the level envisioned in NWNH.	NASA is reviewing options for reduced funding of exoplanet technology development beyond the WFIRST coronagraph, if this is necessary to enable appropriate investments in gravitational wave research and technology.

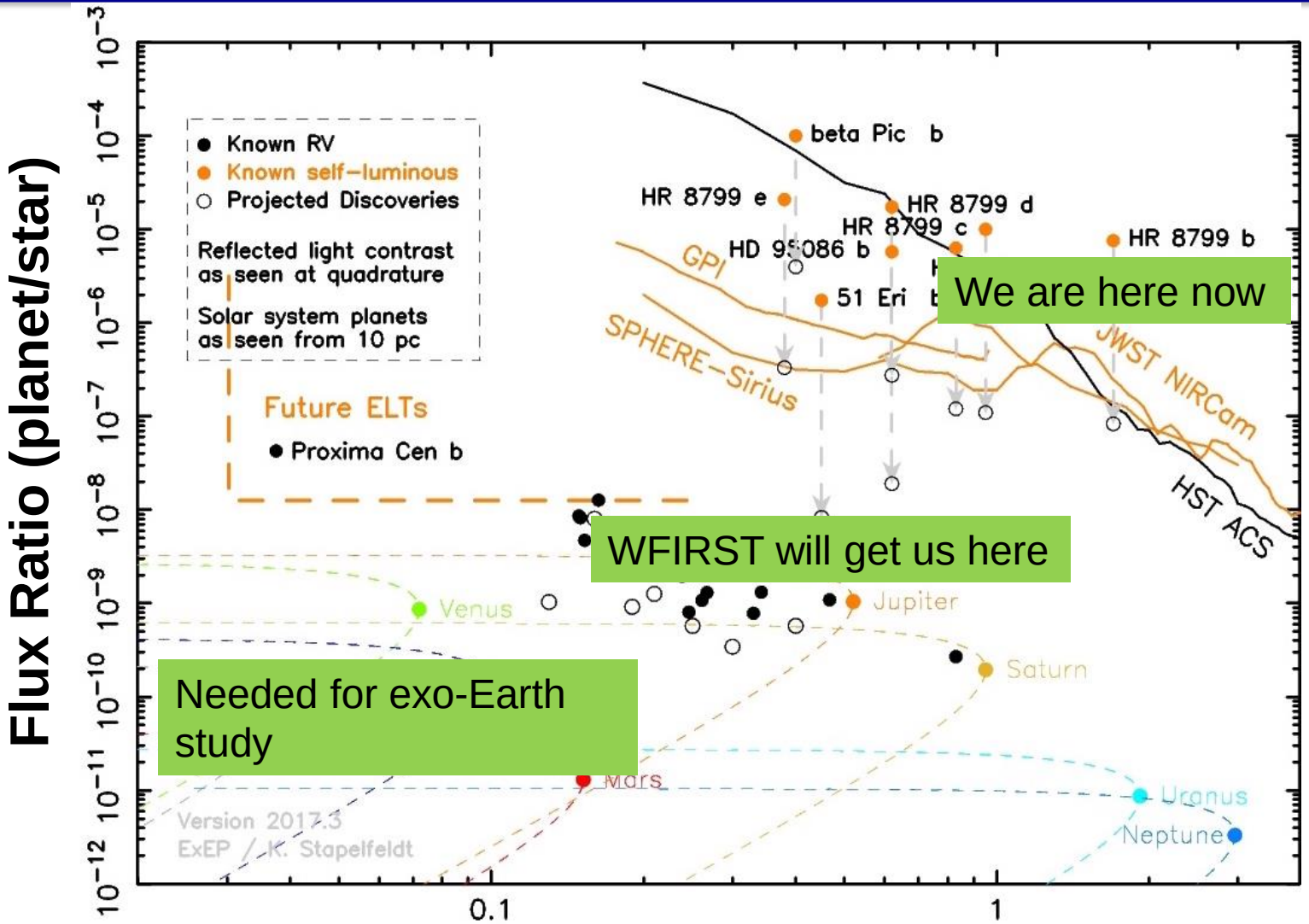
Box 7.1. Midterm Assessment for New Worlds Technology Development.

TABLE ES.4 Space: Recommended Activities—Medium-Scale (Priority Order)

Recommendation	Science	Appraisal of Costs[a]
1. New Worlds Technology Development Program	Preparation for a planet-imaging mission beyond 2020, including precursor science activities	$100M to $200M
2. Inflation Probe Technology Development Program	Cosmic microwave background (CMB)/ inflation technology development and preparation for a possible mission beyond 2020	$60M to $200M

- WFIRST and its CGI are now under a cost cap.
- Slight slow-down in starshade funding in FY17
- All other planned exoplanet technology activities currently on track.

Still a Way to go to Directly Imaging Exo-Earths



Looking Forward:

A Possible NASA Mission Roadmap to the Verification of Life on an Exoplanet

Continued Excitement Over Exoplanets

"All the News That's Fit to Print"

The New York Times

VOL. CLXVI . . . No. 57,517 © 2017 The New York Times Company NEW YORK, THURSDAY, FEBRUARY 23, 2017

JPL-CALTECH/NASA

A rendering of newly discovered Earth-size planets orbiting a dwarf star named Trappist-1 about 40 light-years from Earth. Some of them could have surface water.

Circling a Star Not Far Away,

Uber's Culture Of Gutsiness

Migrants Hide, Fearing Capture on 'Any Corner'

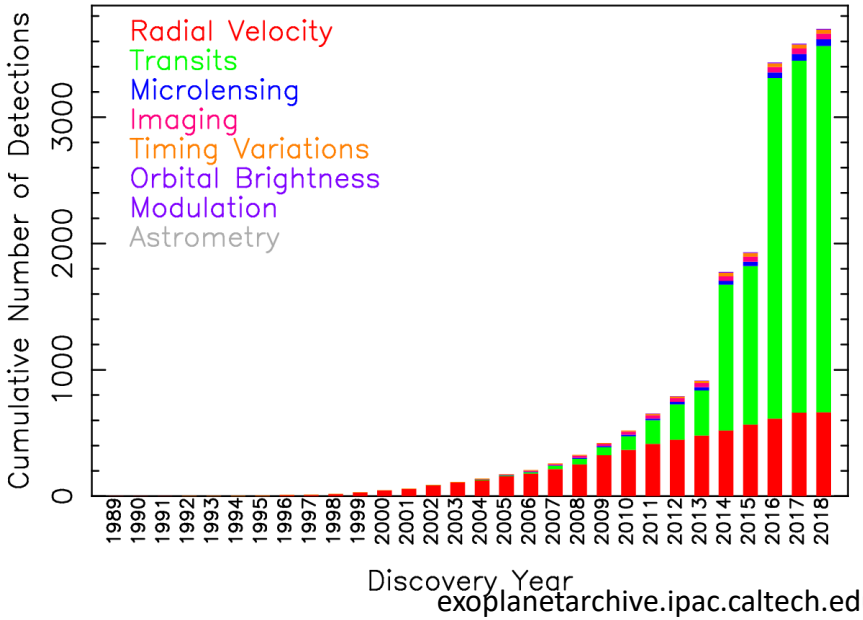
By VIVIAN YEE

IMMIGRATION A police depart-

duras.

If deportation has always been

More than 3700 planets confirmed and counting…

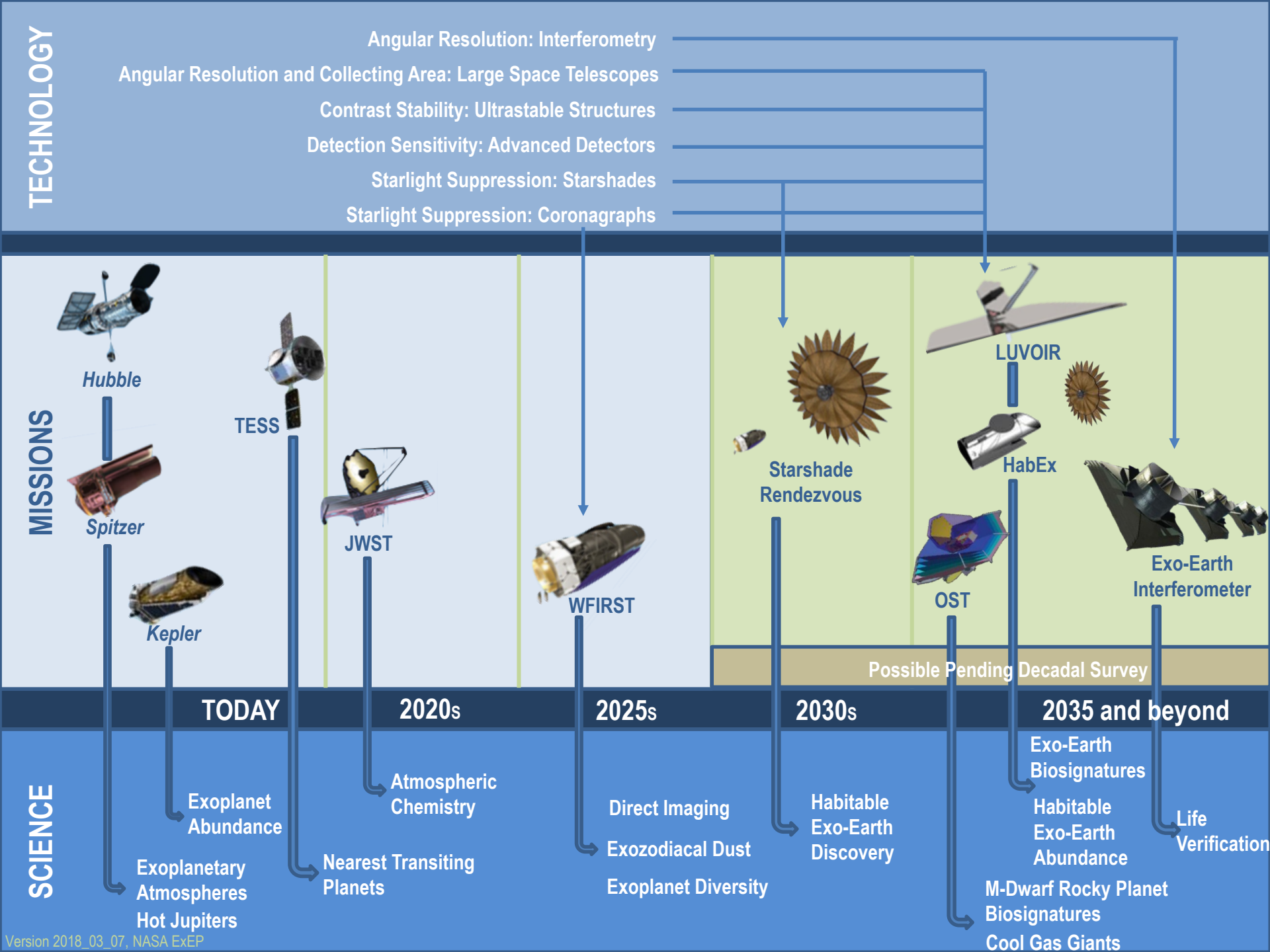


exoplanetarchive.ipac.caltech.edu

… and More on the Way

Credit: NASA

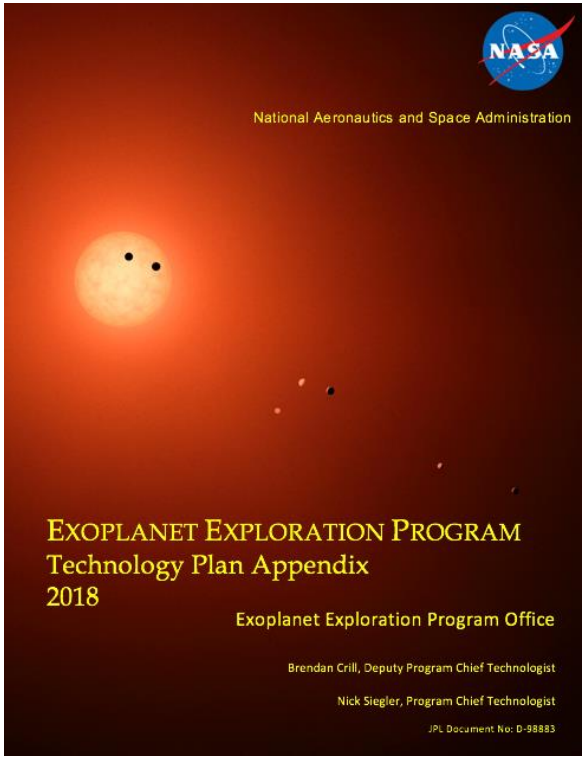
TESS Launch, April 18, 2018


TECHNOLOGY
Angular Resolution: Interferometry
Angular Resolution and Collecting Area: Large Space Telescopes
Contrast Stability: Ultrastable Structures
Detection Sensitivity: Advanced Detectors
Starlight Suppression: Starshades
Starlight Suppression: Coronagraphs
MISSIONS
Hubble
Spitzer
Kepler
TESS
JWST
WFIRST
Starshade Rendezvous
LUVOIR
HabEx
OST
Exo-Earth Interferometer
Possible Pending Decadal Survey
TODAY
2020s
2025s
2030s
2035 and beyond
SCIENCE
Exoplanet Abundance
Exoplanetary Atmospheres
Hot Jupiters
Nearest Transiting Planets
Atmospheric Chemistry
Direct Imaging
Exozodiacal Dust
Exoplanet Diversity
Habitable Exo-Earth Discovery
Exo-Earth Biosignatures
Habitable Exo-Earth Abundance
M-Dwarf Rocky Planet Biosignatures
Cool Gas Giants
Life Verification
Version 2018_03_07, NASA ExEP

Exoplanet Technologies and Technology Gaps

ExEP Technology List

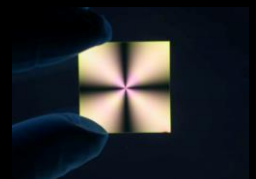
ID	Technology	Technology Gap	Technology Description	Current Capabilities	Needed Capabilities
S-1	**Controlling Scattered Sunlight**	Starshade Contrast	Limit edge-scattered sunlight and diffracted starlight with optical petal edges that also handle stowed bending strain.	Machined graphite edges meet all specs but edge radius (≥ 10 µm); 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 limit solar glint contributing < 10^{-10} contrast at petal edges.



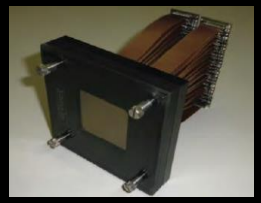
- **14 technology gaps**
- **24 technologies being currently tracked**
- **Technology List posted at:** https://exoplanets.nasa.gov/exep/technology/gap-lists/
- **Technology Plan Appendix posted at:** https://exoplanets.nasa.gov/exep/technology/technology-overview/

V-NIR Coronagraph/Telescope Technology Gaps

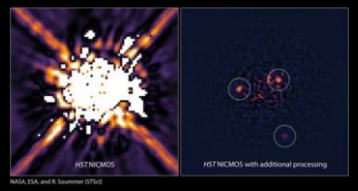
Contrast



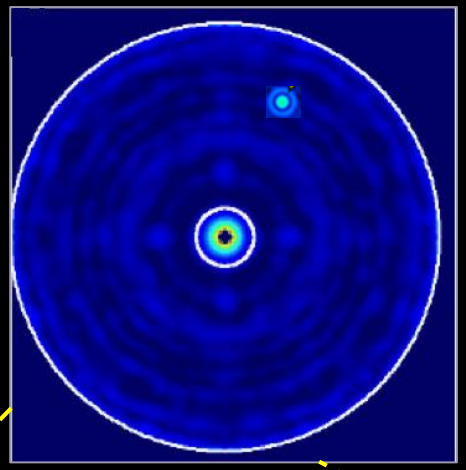
CG-2: Coronagraph Architecture



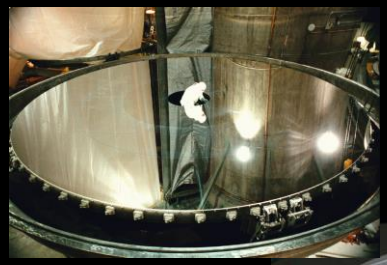
CG-3: Deformable Mirrors



CG-4: Data Post-Processing



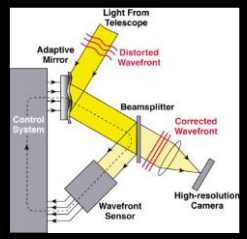
Angular Resolution



CG-1: Large Monolith Mirrors

CG-1: Segmented Mirrors

Contrast Stability

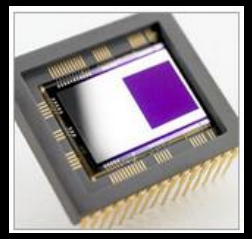


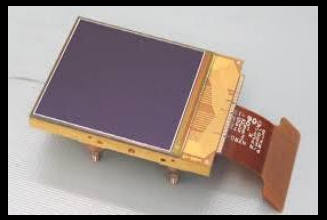
CG-5: Wavefront Sensing and Control

CG-6: Mirror Segment Phasing

CG-7: Telescope Vibration Sensing and Control or Reduction

Detection Sensitivity

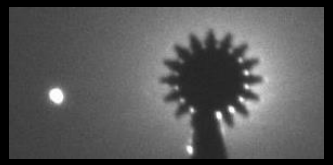




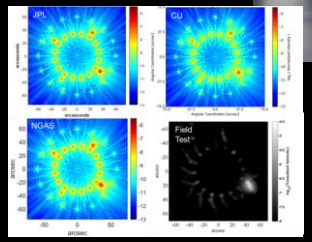
Ultra-low Noise Visible (CG-8) and Infrared (CG-9) Detectors

Starshade Technology Gaps

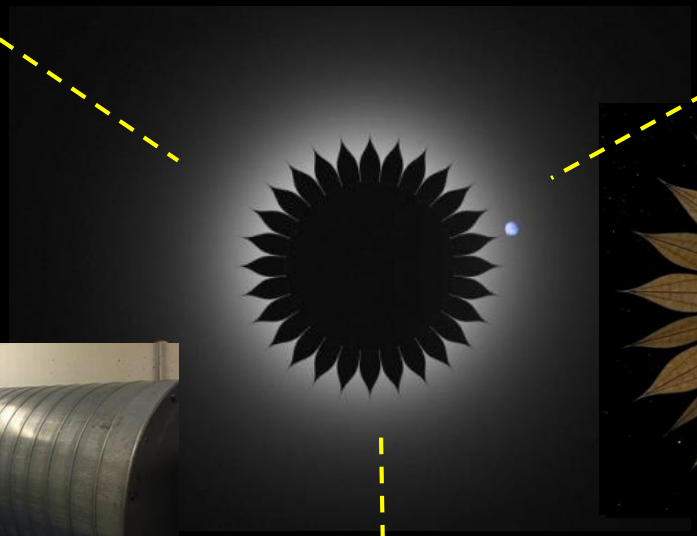
Starlight Suppression



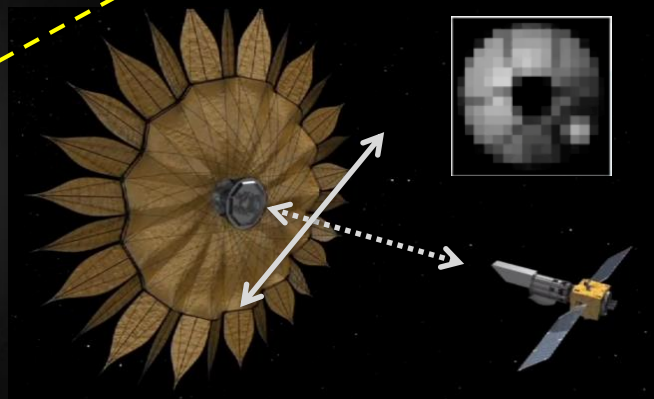
S-1: Controlling Scattered Sunlight



S-2: Starlight Suppression and Model Validation

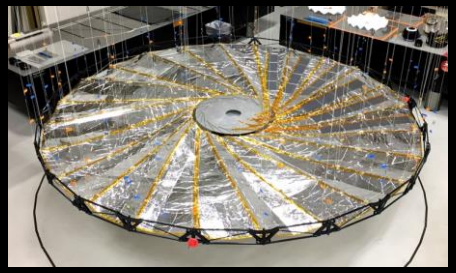


Formation Sensing



S-3: Lateral Formation Sensing

Deployment Accuracy and Shape Stability



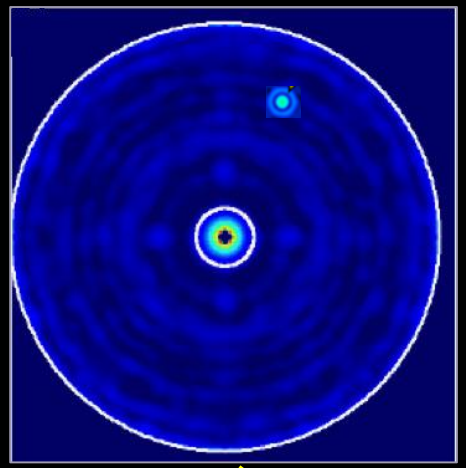
S-4: Petal Shape And Stability

S-5: Petal Positioning Accuracy and Opaque Structure

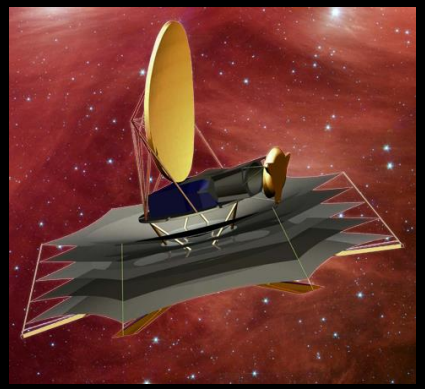
Mid-IR Coronagraph/Telescope Technology Gaps

Contrast

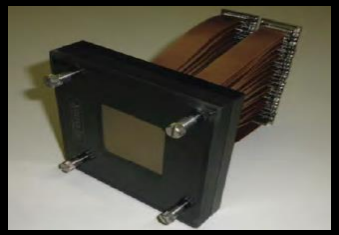
G-15: Mid-IR Coronagraph Optics and Architecture



Angular Resolution

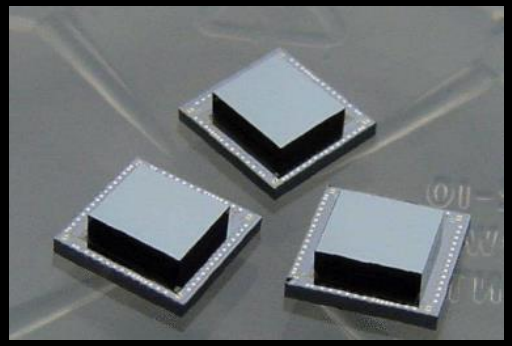


CG-14: Mid-IR Large Aperture Telescopes



CG-16: Cryogenic Deformable Mirror

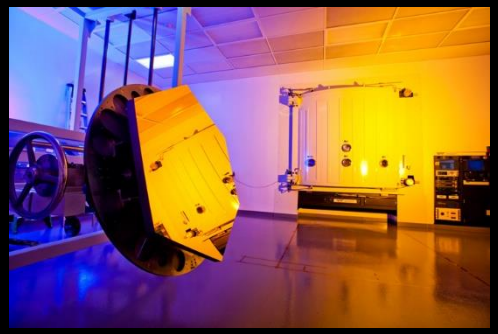
Detection Sensitivity



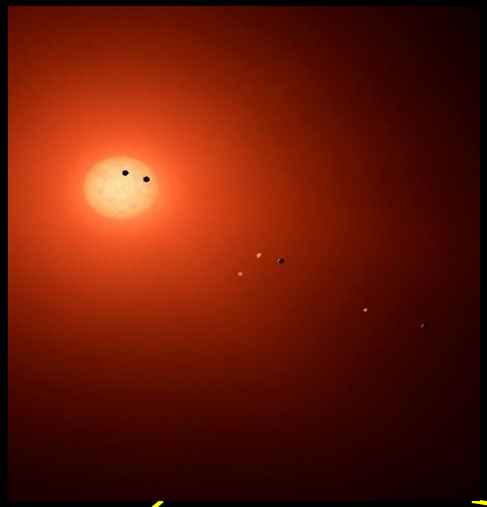
CG-13: Low-Noise Mid-IR Detectors

Other Technology Gaps

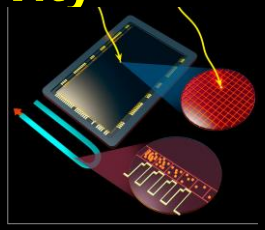
UV Contrast



CG-10 UV/V/NIR Mirror Coatings

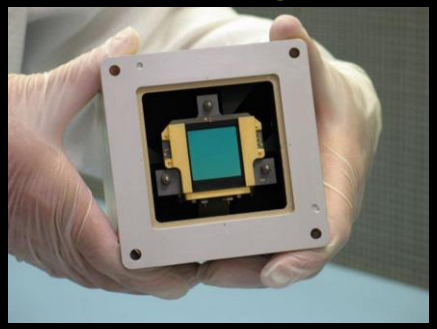


UV Detection Sensitivity



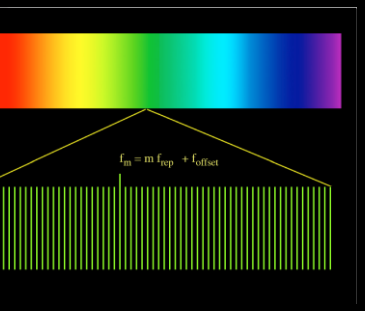
CG-12: Ultra-low Noise UV Detectors

Transit Spectroscopy Sensitivity

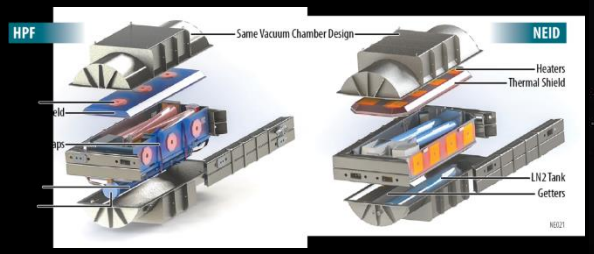


M-4: Ultra-stable Mid-IR Detectors for Transit Spectroscopy

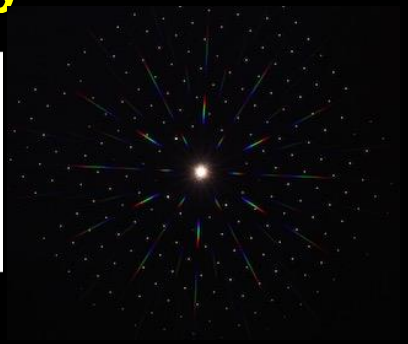
Stellar Reflex Motion Sensitivity



2: Laser Frequency Combs for Space-based EPRV



M-1: Ground-based Ultra-high Precision Radial Velocity



M-3: Astrometry

2018 ExEP Prioritized Technology List

Exoplanet Exploration Program

WFIRST's coronagraph advances state-of-art in multiple technologies

Tech. ID	Technology Title	Impact	Urgency	Trend	2018 Score	2017 Score
	weight:	10	10	5		
CG-2	Coronagraph Architecture	4	4	2	**90**	85
S-2	Starlight Suppression and Model Validation	4	4	2	**90**	90
S-1	Controlling Scattered Sunlight	4	4	2	**90**	90
S-3	Lateral Formation Sensing	4	4	2	**90**	90
S-5	Petal Positioning Accuracy and Opaque Structure	4	4	2	**90**	90
S-4	Petal Shape and Stability	4	4	2	**90**	90
CG-3	Deformable Mirrors	4	4	2	**90**	80
CG-1	Large Aperture Primary Mirrors	4	3	3	**85**	85
CG-6	Mirror Segment Phasing	4	3	3	**85**	85
CG-7	Telescope Vibration Sense/Control or Reduction	4	3	3	**85**	85
CG-9	Ultra-Low Noise Near-Infrared Detectors	4	3	3	**85**	85
CG-5	Wavefront Sensing and Control	4	3	2	**80**	80
CG-8	Ultra-Low Noise Visible Detectors	4	3	2	**80**	80
M-4	Ultra-Stable Mid-IR detector	3	3	4	**80**	
M-3	Astrometry	3	3	3	**75**	
CG-4	Data Post-Processing Algorithms and Techniques	4	2	2	**70**	70
CG-10	Mirror Coatings for UV/NIR/Vis	3	3	2	**70**	70
M-2	Space-based Laser Frequency Combs	3	3	2	**70**	
CG-13	Ultra Low-noise Mid-IR detectors	2	3	4	**70**	
M-1	Extreme Precision Ground-based Radial Velocity	2	3	3	**65**	75
CG-14	Mid-IR Large Aperture Telescopes	2	3	3	**65**	
CG-15	Mid-IR Coronagraph Optics and Architecture	2	3	3	**65**	
CG-16	Cryogenic Deformable mirror	2	3	3	**65**	
CG-12	Ultra-Low Noise UV Detectors	2	3	2	**60**	60

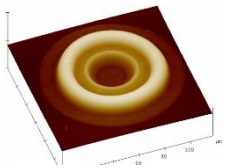
Carried over from 2017
New to list in 2018

WFIRST Coronagraph Technology

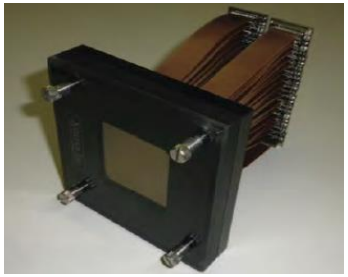
The following technologies are all firsts in space

Exoplanet Exploration Program

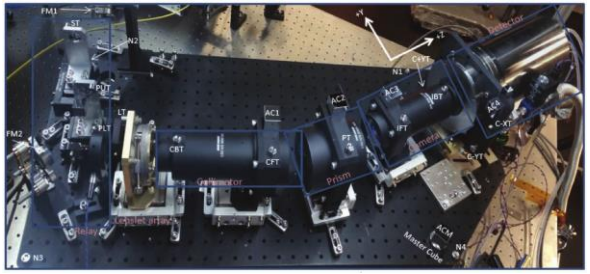
High-contrast coronagraph masks with a highly obscured pupil



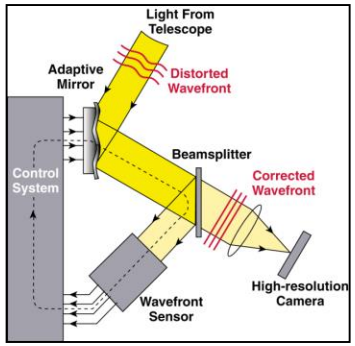
Deformable mirrors



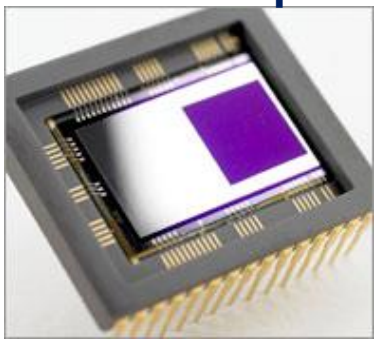
Integral field spectrograph + coronagraph



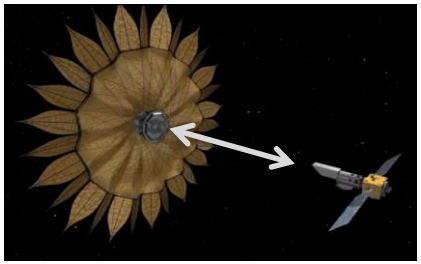
Low order wavefront sense / control



Ultra-low noise EMCCD for space



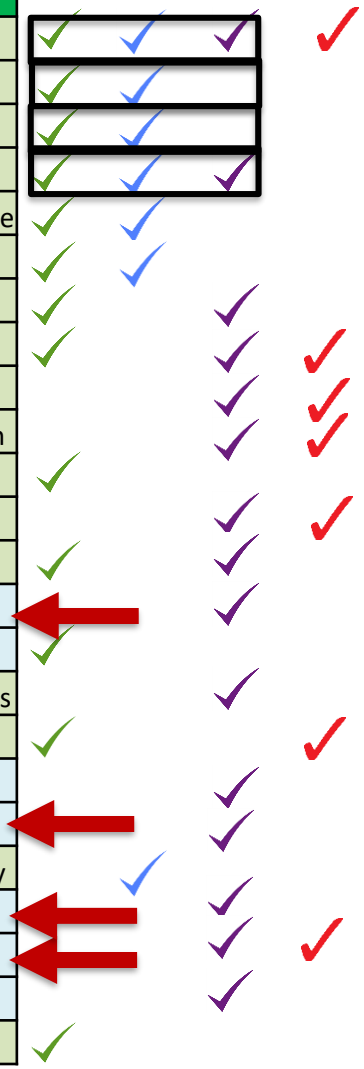
Compatibility with a starshade for possible rendezvous mission pending 2020 Decadal Survey



The reason to fly a coronagraph before a future large exoplanet mission is because it greatly mitigates residual risks, specifically the (1) system-level performance in the operating env't and (2) validation of the performance models and error budgets.

Investments in Exoplanet Technologies

Tech. ID	Technology Title
CG-2	Coronagraph Architecture
S-2	Starlight Suppression and Model Validation
S-1	Controlling Scattered Sunlight
S-3	Lateral Formation Sensing
S-5	Petal Positioning Accuracy and Opaque Structure
S-4	Petal Shape and Stability
CG-3	Deformable Mirrors
CG-1	Large Aperture Primary Mirrors
CG-6	Mirror Segment Phasing
CG-7	Telescope Vibration Sense/Control or Reduction
CG-9	Ultra-Low Noise Near-Infrared Detectors
CG-5	Wavefront Sensing and Control
CG-8	Ultra-Low Noise Visible Detectors
M-4	Ultra-Stable Mid-IR detector
M-3	Astrometry
CG-4	Data Post-Processing Algorithms and Techniques
CG-10	Mirror Coatings for UV/NIR/Vis
M-2	Space-based Laser Frequency Combs
CG-13	Ultra Low-noise Mid-IR detectors
M-1	Extreme Precision Ground-based Radial Velocity
CG-14	Mid-IR Large Aperture Telescopes
CG-15	Mid-IR Coronagraph Optics and Architecture
CG-16	Cryogenic Deformable mirror
CG-12	Ultra-Low Noise UV Detectors



- ✓ SAT / APRA
- ✓ directed
- ✓ mission or mission concept
- ✓ **SMTP** = Segmented Mirror Telescope Program (competed)

funded to TRL 5 *

Mid-IR technologies would benefit from investments to help define the technology requirements

Carried over from 2017
New to list in 2018

* for an exo-Earth imaging mission

Investments in Exoplanet Technologies

Tech. ID	Technology Title
CG-2	Coronagraph Architecture
S-2	Starlight Suppression and Model Validation
S-1	Controlling Scattered Sunlight
S-3	Lateral Formation Sensing
S-5	Petal Positioning Accuracy and Opaque Structure
S-4	Petal Shape and Stability
CG-3	Deformable Mirrors
CG-1	Large Aperture Primary Mirrors
CG-6	Mirror Segment Phasing
CG-7	Telescope Vibration Sense/Control or Reduction
CG-9	Ultra-Low Noise Near-Infrared Detectors
CG-5	Wavefront Sensing and Control
CG-8	Ultra-Low Noise Visible Detectors
M-4	Ultra-Stable Mid-IR detector
M-3	Astrometry
CG-4	Data Post-Processing Algorithms and Techniques
CG-10	Mirror Coatings for UV/NIR/Vis
M-2	Space-based Laser Frequency Combs
CG-13	Ultra Low-noise Mid-IR detectors
M-1	Extreme Precision Ground-based Radial Velocity
CG-14	Mid-IR Large Aperture Telescopes
CG-15	Mid-IR Coronagraph Optics and Architecture
CG-16	Cryogenic Deformable mirror
CG-12	Ultra-Low Noise UV Detectors

✓ SAT / APRA

✓ directed

✓ mission or mission concept

✓ **SMTP** = Segmented Mirror Telescope Program

funded to TRL 5 *

← Technologies benefitting of investment

★ Candidates for technology advancement (based on readiness)

Carried over from 2017
New to list in 2018

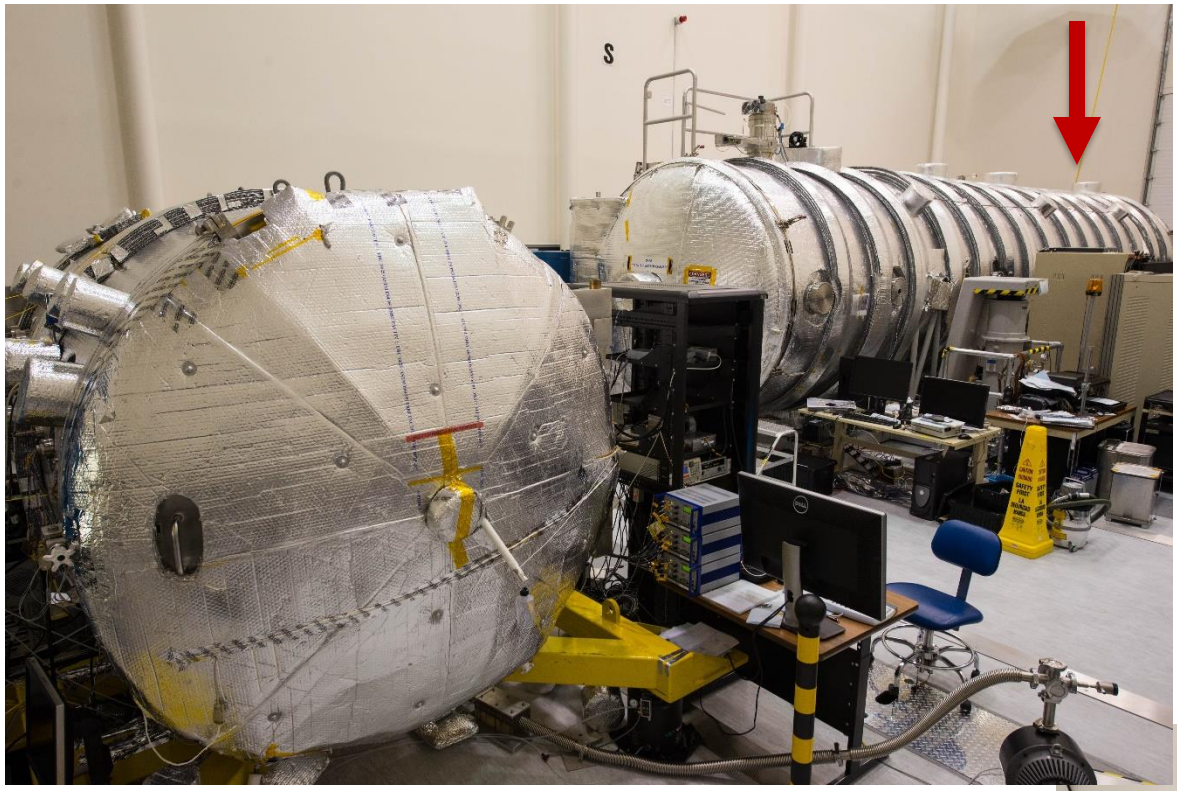
* for an exo-Earth imaging mission

Individual Exoplanet Technology Gap Details

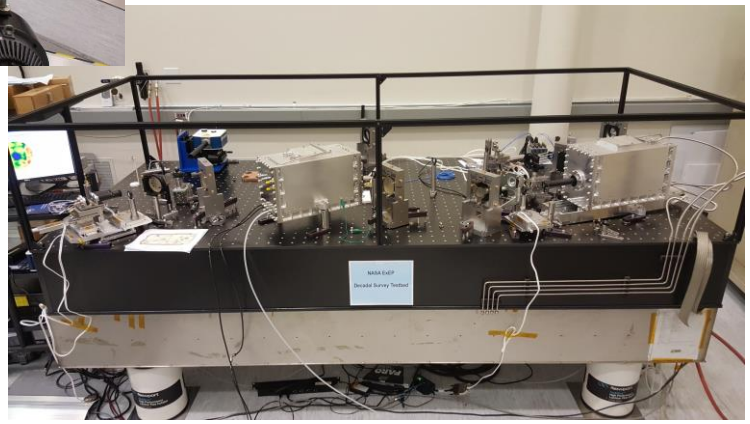
Coronagraph Contrast

- **Need:**
  - maximized science yield for a direct imaging telescope/mission. $\leq 10^{-10}$ raw contrast, >10% throughput, IWA ≤ 3 λ/D, polarization obscured/segmented pupil
- **State of the Art:**
  - unobscured pupil: 6×10^{-10} raw contrast at 10% bandwidth, angles of 3-15 λ/D (HLC demo in HCIT); obscured pupil: $1.6\text{x}10^{-9}$ raw contrast at 10% bandwidth across angles of 3-9 λ/D (WFIRST)
- **Current Efforts:**
  - **ExEP SCDA (Segmented Coronagraph Design & Analysis)**: In CY18 intends to answer:
    1. Can a coronagraph provide high science yield on a segmented telescope while maintaining robustness to wavefront error instabilities and levying realistic requirements on a space telescope?
    2. Can the necessary apodizer masks be built?
  - **ExEP Decadal Survey Testbed (DST)** : In CY18 aims to demonstrate 10^{-10} on a clear aperture, enable future static (CY19) and dynamic (CY20) demos for segmented/obscured apertures
  - **ExEP TDEM** contrast demos in HCIT: Super Lyot (Trauger), PIAACMC (Belikov) aiming for ~10^{-10} contrast demos in HCIT in CY19 and 20, Vortex (Serabyn) aiming for 10^{-9} in CY18
- **Outlook:**
  - PI-led investigations and DST are sufficiently funded to achieve clear-aperture contrast of 10^{-10} in the next 1-2 years.
  - SCDA sufficiently funded to assess performance of segmented/obscured aperture coronagraphs in FY18; off-axis architectures may be required if problems. DST will be available for testing segmented designs in FY19.
  - Look for SCDA results this summer at the SPIE

ExEP Decadal Survey Testbed



High Contrast Imaging Testbed Facility (NASA JPL)



First light in May 2018; deformable mirror installed this summer.

Coronagraph Contrast Stability

- **Need:**
  - Contrast stability on time scales needed for spectral measurements (possibly as long as days). Achieving this stability requires an integrated approach to the coronagraph and telescope, possibly including wavefront sense/control, metrology and correction of mirror segment phasing, vibration isolation/reduction
  - This stability is likely to require wavefront error stability at the level of 10-100 pm per control step (of order 10 minutes).
- **State of the Art:**
  - WFIRST CGI demonstrated ~10^{-8} contrast in a simulated dynamic environment using LOWFS (low-order wavefront sensor) which obtained 12 pm focus sensitivity
  - SIM and non-NASA work has demonstrated nm accuracy and stability with laser metrology
  - Capacitive gap sensors demonstrated at 10 pm
  - 80 dB vibration isolation demonstrated
  - Gaia cold gas microthrusters and LISA pathfinder colloidal microthrusters can reduce vibrations
- **Current Efforts:**
  - LUVOIR and HabEx concept studies are developing reference telescope and coronagraph architectures that are looking to meet these tight stability requirements.
  - SMTP (Segmented Mirror Telescope Program): two industry studies underway
- **Outlook:**
  - Designs and analyses that close are currently being assessed by the large telescope design study teams.
  - Technology is very challenging, especially if the needs are << 100 pm (1-2 orders from SOA)
  - Industry studies very timely, collaboration with STDTs; will guide investments in technologies.

Angular Resolution (UV/O/NIR)

- **Need :**
  - Large (4–15 m) monolith and multi-segmented mirrors for space that meet SFE < 10 nm rms (wavelength coverage 400–2500 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.
- **State of the Art:**
  - Monolith: 3.5-m sintered SiC with < 3 µm SFE (Herschel); 2.4-m 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 3 (AMTD).
  - Segmented: (no flight SOA): 6.5 m 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
- **Current Efforts:**
  - HabEx and LUVOIR studies investigating monolith and segmented architectures, including materials (Si carbide, glass) manufacturing, coating, mounting, thermal control, vibration isolation.
  - SMTP studies are investigating manufacturability of large segmented mirrors with industry
  - In-space assembly of future large telescopes under study
- **Outlook:**
  - Readiness depends on size and requirements of telescope for a given mission.
  - Coronagraph drives requirements for large space telescopes: science yield, in particular Earth-sized planets, of a coronagraph instrument may drive towards a larger primary mirror size
  - Availability of SLS enables launch of existing monolith mirror technology up to 4 m and beyond.
  - STDT design studies and SMTP industry studies will identify next technology investments

Visible/NIR Detection Sensitivity (1/2)

- **Need :**
  - Near IR (900 nm to 2.5 μm) and visible-band (400-900nm) extremely low noise detectors for exo-Earth spectral characterization with Integral Field Spectrographs. NIR Read noise << 1 e- rms, dark current noise < 0.001 e-/pix/s, Vis band read noise < 0.1 e- rms; CIC < 3×10^{-3} e-/px/frame; dark current < 10^{-4} e-/px/sec , functioning in a space radiation environment over mission lifetime; large ≥ 2k×2k format.
- **State of the Art:**
  - Vis: 1k×1k silicon EMCCD detectors provide dark current of 7×10^{-4} e^-/px/sec; CIC of 0.01 e^-/px/frame; zero effective read noise (in photon counting mode) after irradiation when cooled to 165.15 K (WFIRST); 4k×4k EMCCD fabricated but still under development
  - NIR: HgCdTe photodiode arrays have read noise $\lesssim$ 2 e- rms with multiple nondestructive reads; 2k×2k format; 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 < 1k×1k format
  - Cryogenic superconducting photon-counting detectors (MKID,TES): 0 read noise/dark current; radiation tolerance is unknown; <1k×1k format
- **Current Efforts:**
  - HabEx and LUVOIR have baselined existing EMCCD (Vis) and HgCdTe (NIR) detectors while keeping an eye on potential improvements in other areas, particularly in read noise, dark current and radiation hardness
  - WFIRST CGI is advancing the EMCCD technology for the Vis band, in particular aiming to improve radiation hardness
  - Superconducting detectors (MKID, TES, etc.) developing under APRA for sub-orbital and ground-based efforts

Visible/NIR Detection Sensitivity (2/2)

- **Outlook:**
  - Readiness of this technology to be judged against specific mission goals but mission lifetime as determined by radiation hardness is the biggest issue for the visible EMCCDs (advanced through CGI).
  - In the NIR, current designs are selecting existing HgCdTe NIR detectors. However, reducing read noise and read-out electronics would further enable greater detector sensitivity and hence lower integration times. Advancing APDs is another way of reducing read noise but then you have a dark current problem
  - NIR detector technology gap would benefit from further investment.

Starshade Starlight Suppression and Model Validation

- **Need:**
  - Experimentally validate at flight-like Fresnel numbers (F) the equations that predict starshade starlight suppression: total starlight suppression ≤ 10^{-8} in scaled flight-like geometry, F between 5 and 40 across a broadband optical bandpass. Validated models are traceable to 10^{-10} contrast system performance in space.
  - Limit edge-scattered sunlight and diffracted starlight with optical petal edges that also handle any stowed bending strain. Limit solar glint contributing < 10^{-10} contrast at petal edges.
- **State of the Art:**
  - Validated optical model with demonstrated 10^{-6} suppression at white light, 58 cm mask, and F (at the starshade tips) = 210; 6×10^{-6} suppression demonstrated at F =15; 4.6×10^{-8} suppression demonstrated at F ~ 27
  - Etched amorphous metal edges meet scatter specs integrated in-plane shape tolerance is to be demonstrated.
- **Current Efforts:**
  - Sub-scale tests at Princeton expected to achieve flight suppression. Current limits are set by the subscale star
  - Amorphous metal edges are being demonstrates to meet shape requirements.
- **Outlook:**
  - Optical edges and model validation are funded to reach TRL 5 by FY22
  - Suppression demos are high priority for S5 (name of Starshade Technology Development Activity)
  - Because of reliance on models, once flight-like suppression is demonstrated, should also validate equations in a slightly wider range of parameters (wavelengths, subscale starshade size, etc.)
  - The edge scatter technology scheduled to be at TRL 5 by the S5 project in 1-2 years

Starshade Formation Sensing

- **Need :**
  - Demonstrate sensing lateral errors ≤ 0.24 m 3σ accuracy at the flight signal-to-noise ratio at scaled flight separations. Demonstrate control algorithms with scaled lateral control error ≤ 1m radius.
- **State of the Art:**
  - Sub-scale lab demonstration showing ability to center telescope within ± 1 m of starshade shadow.
- **Current Efforts:**
  - WFIRST starshade accommodation and S5 created a scaled benchtop demonstration of using an out-of-band pupil-plane camera (for WFIRST, the LOWFS camera will suffice) to provide misalignment sensing
  - Control algorithms based on the sensor are also to be demonstrated at subscale.
- **Outlook:**
  - Formation sensing is funded to reach TRL 5 in FY19 for a potential WFIRST Rendezvous concept
  - The pupil-plane camera approach will be roughly independent of starshade and telescope diameter

Starshade Deployment and Shape Stability

- **Need:**
  - A system that will deploy the petals from a launch-stowed configuration to the needed shape (to better than ≤ 1 mm (in-plane envelope) and maintain petal edges to ≤ 100 μm (in-plane tolerance profile for a 7 m petal on the 34 m-diameter Exo-S design; tolerances scale roughly linearly with starshade diameter), and be optically opaque.
- **State of the Art:**
  - Manufacturing tolerance (≤ 100 μm) verified with low fidelity 6 m prototype petal and no environmental tests. Petal deployment tests conducted but on prototype petals to demonstrate rib actuation; no shape measurements, no long-duration stowage tests.
  - Petal deployment tolerance (≤ 1 mm) verified with low fidelity 12 m prototype and no optical shield; no environmental testing (Exo-S design).
- **Current Efforts:**
  - Deployment trade study is nearing its end. It will select a deployment architecture to use as a baseline towards reaching TRL 5 by FY22.
  - Work on this mechanical deployment will accelerate after trade study is complete.
- **Outlook:**
  - Technologies to close this gap for a WFIRST rendezvous design (30 m-diameter class starshade) are funded to reach TRL 5 by FY22
  - A larger starshade (> 70 m) will require additional technology development for both petal stability and deployment accuracy.

Mid-IR Contrast

- **Need :**
  - Coronagraphy in the mid-IR to detect ~100-300K giant planets in emission and perform spectroscopy between 10-30 um wavelength, with 2 λ/D inner working angle and of order 10^{-6} contrast. Maximum spectral dispersion should be sufficient to resolve the 15 um CO_2 band (R ~ 500).
- **State of the Art:**
  - The current state of the art for mid-IR coronagraphs are the three four-quadrant phase masks of JWST-MIRI. These provide narrow-band imaging with contrasts up to 10^{-4} in three narrow bands from 10.65-15.5 um with inner working angles of 0.33-0.49”. The MIRI coronagraphs do not offer spectral dispersion.
- **Current Efforts:**
  - OST is currently studying the science case for mid-IR coronagraphy and technology development needed to achieve the science goals.
  - JAXA is studying the mid-IR instrument (MISC) in OST.
  - If OST uses a segmented telescope, this technology may benefit from the SCDA study.
- **Outlook:**
  - OST’s final reports will better define these technology needs and thus the state of readiness.
  - The relatively modest contrast may not require small deformable mirrors such as those needed for speckle nulling in the visible band. If this is the case, this coronagraph could be ready on the time scale of a Vis/NIR coronagraph.
  - Learning from MIRI; no other funding currently.

Ultra-Stable Mid-IR Detectors for Transit Spectroscopy

- **Need :**
  - Ultra-stable detectors (< 10 ppm over 5 hours) for the mid-IR band (7 - 20 um) enabling transit spectroscopy of rocky exoplanets in the Habitable Zone of M-dwarfs.
- **State of the Art:**
  - JWST/MIRI is expected to achieve 10-100 ppm transit stability.
  - Spitzer IRAC Si:As detector data have demonstrated about 60 ppm precision in transit observations of several hours
- **Current Efforts:**
  - OST is currently studying the science case for transit spectroscopy and technology development needed to achieve the science goals.
  - OST is developing a Detector Technology Roadmap, including mid-IR detectors with these stability requirements.
  - Analysis of MIRI transit spectroscopy data when JWST on-orbit performance will provide additional lessons
- **Outlook:**
  - The needs specified in OST's final report will determine the current level of readiness, and the OST technology roadmap will present a plan to reach the needed level of performance.
  - Development of band-impurity-type detectors may require re-building an industrial base.
  - This is a very challenging technology.

Mid-IR Angular Resolution

- **Need :**
  - Actively cooled cryogenic (4 K), large-aperture (> 9 m) telescopes to achieve high angular resolution needed to direct-image cool exoplanets in wide orbits (> 5 AU).
- **State of the Art:**
  - JWST is not actively cooled at 45 K
  - Hershel 3.5 m SiC-sintered monolith telescope
  - JWST Be mirror segments may meet requirements now, but other materials like SiC or simply aluminum may. Cryogenic low-dissipation actuators may play a role if active surface figuring is deemed necessary
- **Current Efforts:**
  - OST studying telescope requirements.
  - Active cryogenic SiC mirror segments being studied
  - SMTP (Segmented Mirror Telescope Program) industry study is investigating manufacturability of large cryogenic segmented mirrors.
- **Outlook:**
  - Large (> 9 m) cryogenic telescopes are fairly far from being ready (actively-cooled and segmented).
  - Current efforts appear appropriate at this time.

Mid-IR Detection Sensitivity

- **Need :**
  - Low noise detectors for the mid-IR band (7 - 20 um) enabling exoplanet direct imaging. Noise requirements are TBD, likely to be 10x better than JWST/MIRI.
- **State of the Art:**
  - JWST/MIRI's band-impurity detectors is the state of the art in this wavelength band.
- **Current Efforts:**
  - Watch and wait MIRI (performance on orbit will set the state of the art in this band).
  - NeoCAM is developing H2RGs with sensitivity at wavelengths as long as 12 um.
  - OST will study sensitivity needs for their coronagraph; developing a Detector Technology Roadmap.
- **Outlook:**
  - The needs specified in OST's final report and the Detector Roadmap will determine the current level readiness.
  - If improvement is needed in band-impurity-type detectors, building up an industrial base may be needed.

UV Contrast

- **Need :**
  - Mirror coatings that enable high reflectivity to wavelengths as short as 90 nm while maintaining good performance in the Visible and NIR bands
  - Coating uniformity must be good enough that polarization phase and amplitude difference < 1% between orthogonal polarization states across the whole band.
- **State of the Art:**
  - Al coating with combination of MgF_2, LiF, and/or AlF_3 overcoat: 90-120 nm: < 50% reflectivity 120-300 nm: 85% reflectivity 300 nm-2 µm: > 90% reflectivity Polarization differences between orthogonal polarization states, uniformity, and durability of coatings on large optics is unknown. Flight: HST uses MgF_2; 85% reflectivity λ> 120 nm; 20% reflectivity λ < 120 nm
- **Current Efforts:**
  - HabEx and LUVOIR studies are both looking into trading ability to do coronagraphy across a wide band while maintaining UV sensitivity.
  - TDEM-funded study (PI Breckinridge) looking into sensitivity of polarization aberrations and may set requirements from a coronagraph on coating uniformity.
- **Outlook:**
  - Telescope coatings for wavelengths > 120 nm could be ready now if uniformity is acceptable.
  - If STDT goes < 120 nm then technology development would be required

UV Detection Sensitivity

- **Need :**
  - Low-noise ultraviolet (200-400 nm) detectors to characterize exoplanets with an integral field spectrograph.
  - Read Noise: 0 e-; Dark Current: 0 e- /resolution/s; Spurious Count Rate: < 0.05 counts/cm2/s; QE: 75% ; Resolution size ≤ 10 mm; Tolerant to space radiation environment over mission lifetime.
- **State of the Art:**
  - Lab: Micro-channel Plates (MCP): 0 read noise, 90 – 300 nm, spurious count rate 0.05 - 0.5 counts/cm^2/s; QE 20-45%; resolution element size 20 mm. EMCCD: 0 read noise, dark current > 0.005 e-/res/hr; QE 30-50%; resol. el. size 20 mm Flight: HST HRC: In relevant UV band (250 nm): QE 33%, read noise 4.7 e-, dark current 5.8×10^{-3}, 1024x1024
- **Current Efforts:**
  - LUVOIR and HabEx studies determining whether these detectors are already good enough for their needs.
  - APRA and SAT awards are advancing these detectors.
- **Outlook:**

  - These detectors are likely to be ready within a few years

Stellar Reflex Motion Sensitivity: Radial Velocity

- **Need:**
  - Capability to measure exoplanet masses down to the Earth-mass level. The radial velocity semi-amplitude of a Solar-mass star due to an orbiting Earth-mass planet at 1 AU is 9 cm/s, hence we need RV measurements at the roughly 1 cm/s level of precision.
  - Technology to make radial velocity mass measurements may include using a space-based instrument to avoid atmospheric telluric lines, and simultaneous measurements of stellar lines across a broad band (both Vis and NIR)
  - Theoretical understanding of astrophysical noise sources (stellar jitter) and how to mitigate them
- **State of the Art:**
  - Ground-based RV: The state-of-the art single measurement precision is currently 80 cm/s.
  - Laser frequency combs demonstrated on ground-based observatories with correct mode spacing, non-NASA work is advancing miniaturization. Fiber laser-based optical frequency combs demonstrated on sounding rocket though with closer line spacing than useful for RV.
- **Current Efforts:**
  - NASA-chartered probe study investigating benefits of RV instrument on a space telescope
  - Ground-based RV instruments are expected to achieve 20-30 cm/s by NN-EXPLORE's NEID instrument (WIYN telescope) and the iLocator instrument (LBT), both planned for 2018-2019
- **Outlook:**
  - Error budgets from ground-based NN-EXPLORE's NEID and iLocator will help to guide investments for future precision from the ground; probe study will help with space requirements.
  - The community needs an effort to advance theoretical understanding of stellar noise and how to suppress it (candidate for further investment)
  - Candidate for potential technology investments.

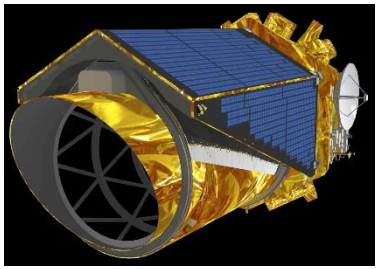
Stellar Reflex Motion Sensitivity: Astrometry

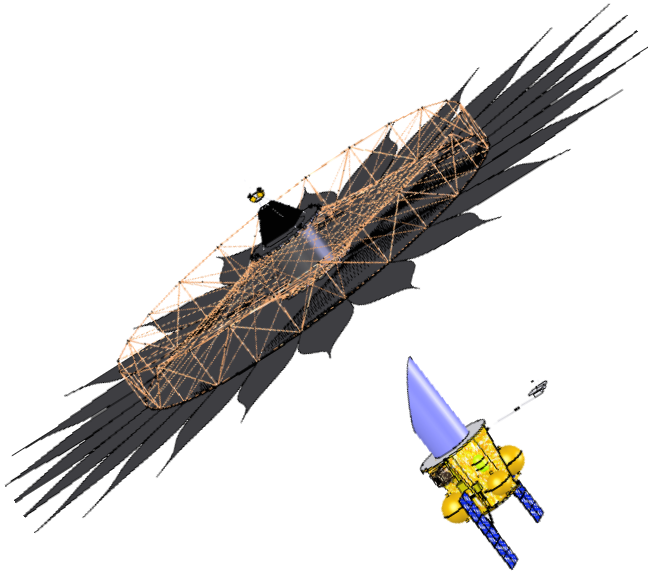
- **Need:**
  - Capability to measure exoplanet mass down to the Earth mass level. Astrometric detection of an exo-Earth at 10 pc requires 0.1 microarcsecond precision.
  - Technology with the stability needed to make astrometric measurements at this level, possibly requiring detector metrology and/or diffractive pupils.
  - Theoretical understanding of astrophysical noise sources (star spots) and how to mitigate them
- **State of the Art:**
  - Gaia preliminarily estimated to achieve 34 microarcsecond measurement error, but ultimately could achieve 10 microarcseconds on bright targets after all systematics are calibrated.
  - TDEM-funded demonstration (Bendek) of diffractive pupil approach demonstrated 5.75×10^{-5} l/D, or 1.4 microarcsecond on a 4 m telescope (limited by detector calibration)
  - Preliminary study of 1 m space telescope and instrument with in-situ detector calibration can achieve 0.8 microarcsec in 1 hr observation (see Shao et al Whitepaper)
- **Current Efforts:**
  - None
- **Outlook:**
  - Technologies are thought to be relatively mature (to be confirmed)
  - Theoretical understanding is needed of stellar noise (confusion due to star spots)
  - Candidate for potential technology investment

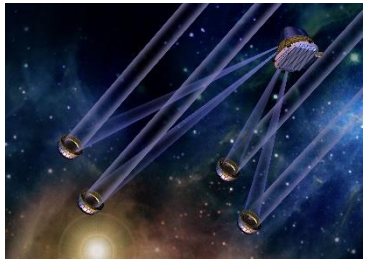
Acknowledgements

This work was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration

© Copyright 2018 California Institute of Technology; Government sponsorship acknowledged



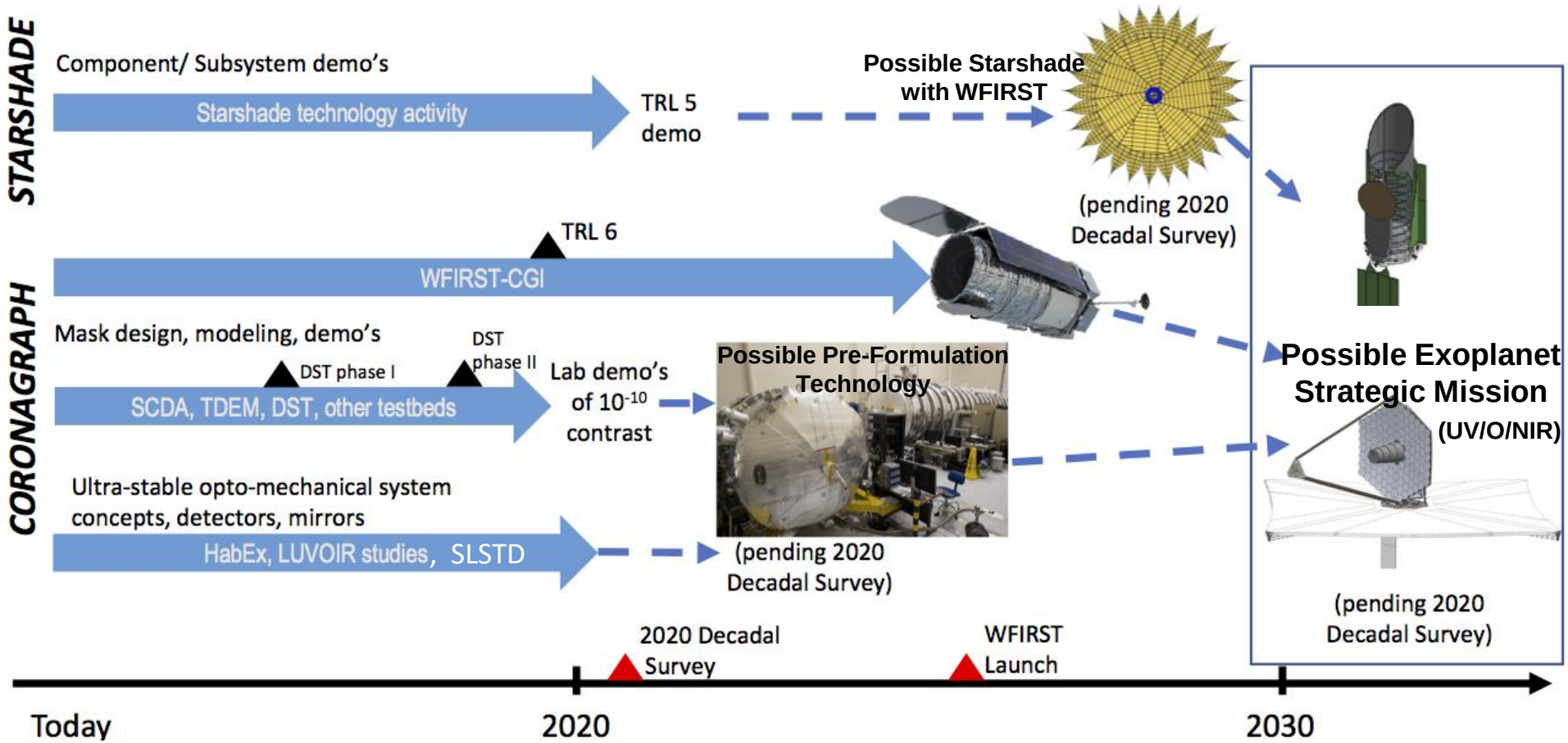




ADDITIONAL SLIDES

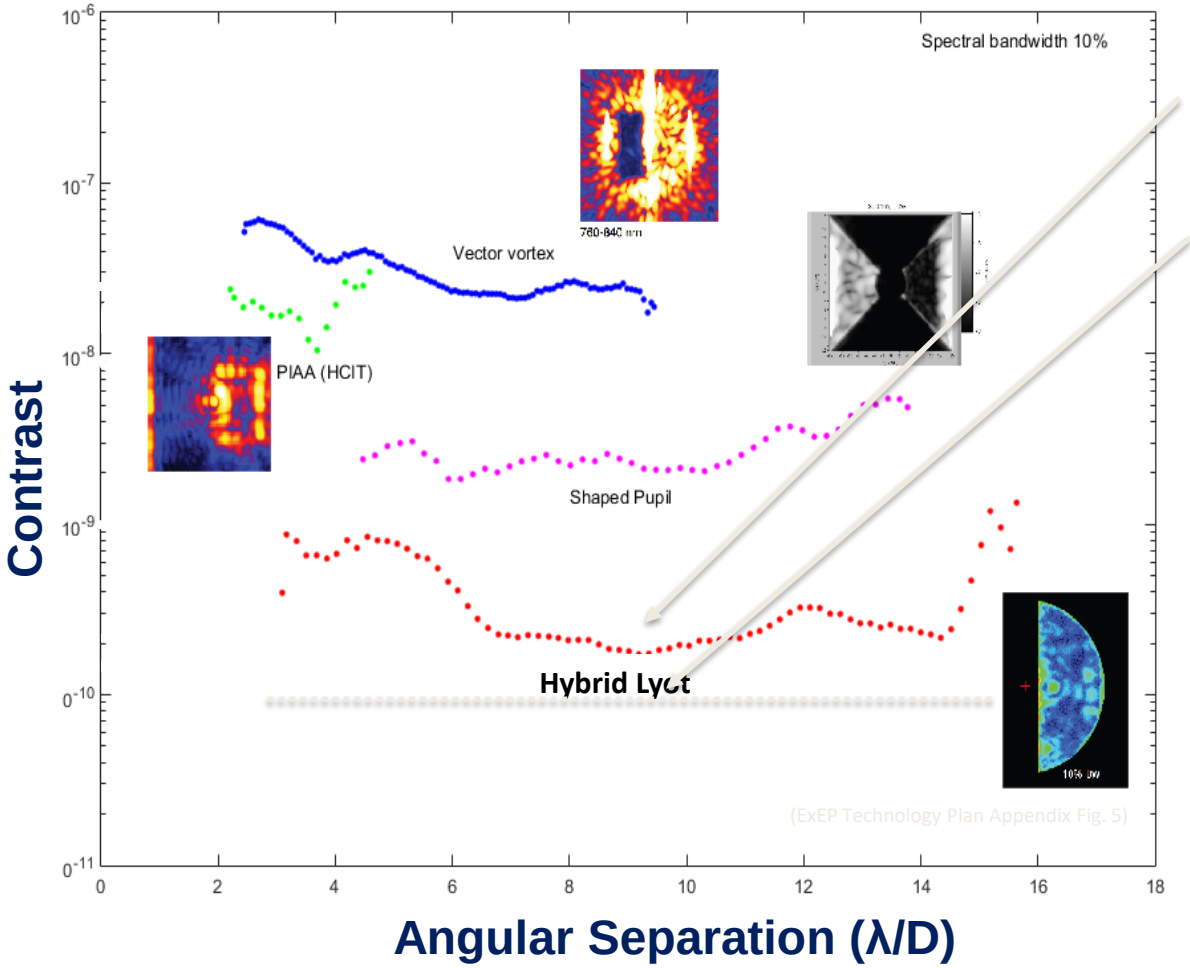
Possible Technology Path to Imaging an Exo-Earth

Exoplanet Exploration Program



SLSTD = System-Level Segmented Telescope Design, **SCDA** = Segmented Coronagraph Design & Analysis, **DST** = Decadal Survey Testbed, **CGI** = Coronagraph Instrument, **TDEM** = Technology Demonstrations for Exoplanet Missions

ExEP Decadal Survey Testbed



Current best contrast demonstration with 10% band (Trauger (JPL)

<u>Decadal Survey Testbed</u>

Phase I: meet 10^{-10} contrast with 10% band and a clear aperture in 2018

Phase II: replace clear pupil with a segmented/obscured (static) aperture in 2019

Phase III: replace static aperture with a dynamic segmented/obscured telescope simulator in 2020

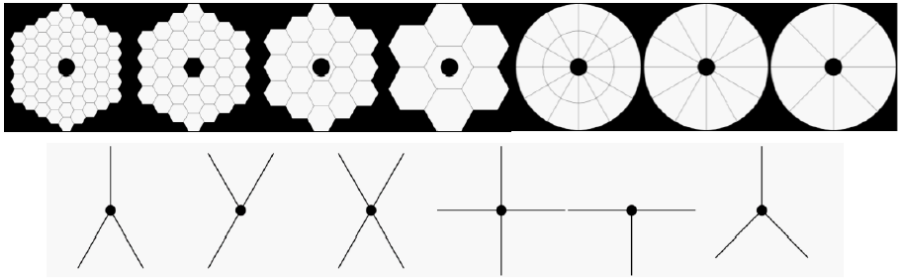
Technology Prioritization Weighting

Impact, Urgency, Trend

Impact: (weight: 10)	4: Critical strategic technology for the New Worlds Technology Development Program envisioned in *New Worlds, New Horizons* (2010 Decadal Survey) and in the NASA Astrophysics Implementation Plan; without this technology, the mission would not launch.
	3: Highly desirable – not mission-critical, but provides major benefits in enhanced science capability, reduced critical resources need, and/or reduced mission risks; without it, missions may launch, but science or implementation would be compromised.
	2: Desirable – not required for mission success, but offers significant science or implementation benefits; if technology is available, would almost certainly be implemented in missions.
	1: Minor science impact or implementation improvements; if technology is available would be considered for implementation in missions.
Urgency (weight: 10)	4: Advances technology or reduces risk needed for missions currently in Pre-Formulation or formulation.
	3: In time to inform the 2020 Decadal Survey; not necessarily at some TRL but reduced risk.
	2: Earliest projected launch date < 15 yr (< 2033).
	1: Earliest projected launch date > 15 yr (> 2033).
Trend (weight: 5)	4: (a) no ongoing current efforts, or (b) little or no funding allocated.
	3: (a) others are working towards it but little results or their performance goals are very far from the need, (b) funding unclear, or (c) time frame not clear.
	2: (a) others are working towards it with encouraging results or their performance goals will fall short from the need, (b) funding may be unclear, or (c) time frame not clear.
	1: (a) others are actively working towards it with encouraging results or their performance goals are close to need, (b) it's sufficiently funded, and (c) time frame clear and on time.

The ExEP Segmented Coronagraph Design and Analysis (SCDA) Study

- SCDA study is evaluating coronagraph designs for future large on-axis, segmented space telescopes



- Groups at Arizona, Ames, GSFC, STScI, JPL, Caltech, are designing coronagraphs to achieve 10^{-10} contrast -> <u>maximize scientific yield</u>

- Evaluate designs against a common set of metrics (such as robustness, manufacturability, does coronagraph place unrealistic demands on telescope)

- APLC design so far is the most successful architecture, though obtaining excellent throughput and IWA is still a challenge

2018 Technology Selection and Prioritization Process Results

- **In the 2017 Technology Plan Appendix, we had 18 items on the prioritized Technology List and 4 on the Watch List**

- **In summer 2017, we received 37 technology inputs from the community**
  - 14 from LUVOIR STDT
  - 15 from HabEx STDT
  - 4 from OST STDT
  - 2 from community at large
  - 2 redirected from COR

- **Disposition:**
  - None were rejected
  - 32 were consolidated into existing technologies already on the List
  - 5 new additions to the Technology List
  - 2 from Watch List upgraded to the Technology List
  - 0 additions to the Watch List
  - 1 listed technology was broken down into 3 finer component/subsystem technologies

- **There are now 24 technologies on the 2018 prioritized list and 2 on the Watch List https://exoplanets.nasa.gov/exep/technology/gap-lists/**

ExEP Technology Selection and Prioritization Process

New technology recommendations from exoplanet community

Technologies carried over from previous year

Selection Criteria: Enables or enhances detection or characterization of exoplanets?

No

Not accepted

No, but could still benefit exoplanet science

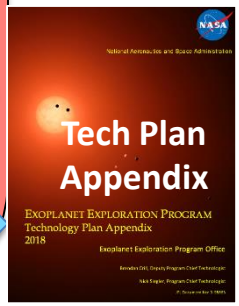
Watch List

Yes

Accepted and Prioritized: Impact, Urgency, and Trend

Reviewed by
(1) APD Program Offices and
(2) Exo-TAC

ExEP Technology List

Reviewed by Exo-TAC

Informs SAT/TDEM Call