Technology Activities (in a snapshot)

Technology Gaps

Strategic Astrophysics Technology Grants
- Coronagraph architectures: modeling and demonstrations
- Wavefront control
- Extreme Precision Radial Velocity
- Detectors

Ultra-Stable Coronagraph Testbeds

Deformable Mirror Survey

Extreme Precision Radial Velocity

Starshade Technology Development

Segmented Coronagraph Design & Analysis Study

Roman/CGI
2010 Decadal Survey

New Worlds, New Horizons in Astronomy and Astrophysics

2020 Decadal Survey expected in spring 2021

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

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

### Tier 1 Technology Gaps
- Angular Resolution (UV/Vis/NIR)
- Coronagraph Contrast
- Coronagraph Contrast Stability
- Cryogenic Readouts for Large-Format Far-IR Detectors
- Fast, Low-Noise, Megapixel X-Ray Imaging Arrays with Moderate Spectral Resolution
- High-Efficiency X-Ray Grating Arrays for High-Resolution Spectroscopy
- High-Resolution, Large-Area, Lightweight X-Ray Optics
- Large-Format, High-Resolution, UV/Vis Focal Plane Arrays
- Large-Format, High-Spectral-Resolution, Small-Pixel X-Ray Focal-Plane Arrays
- Large-Format, Low-Noise and Ultralow-Noise Far-IR Direct Detectors
- Large-Format, Low-Noise, High- QE Far-UV Detectors
- Next-Generation, Large-Format, Object Selection Technology for Multi-Object Spectrometers for LUVOR
- Vis/NIR Detection Sensitivity

### Tier 2 Technology Gaps
- Advanced Millimeter-Wave Focal-Plane Arrays for CMB Polarimetry
- Detection Stability in Mid-IR
- Heterodyne FIR Detector Arrays and Related Technologies
- High-Efficiency Object Selection Technology for UV Multi-Object Spectrometers
- High-Performance Spectral Dispersion Component/Device
- High-Reflectivity Broadband FUV-to-NIR Mirror Coatings
- High-Throughput Bandpass Selection for UV/Vis
- Large-Format Object Selection Technology for Multi-Object Spectrometers for HabEx
- Starshade Deployment and Shape Stability
- Starshade Starlight Suppression and Model Validation
- Stellar Reflex Motion Sensitivity – Astrometry
- Stellar Reflex Motion Sensitivity – Extreme Precision Radial Velocity

### Tier 3 Technology Gaps
- Advanced Cryocoolers
- High-Performance, Sub-Kelvin Coolers
- Large Cryogenic Optics for the Mid-IR to Far-IR
- Long-Wavelength-Blocking Filters for X-Ray Micro-Calorimeters
- Low-Noise, High-QE UV Detectors
- Low-Stress, Highly Stable X-Ray Reflective Coatings
- Photon-Counting, Large-Format UV Detectors
- Polarization-Preserving Millimeter-Wave Optical Elements
- UV Coatings
- UV Detection Sensitivity
- UV/Vis/NIR Tunable Narrow-Band Imaging Capability
- Warm Readout Electronics for Large-Format Far-IR Detectors

### Tier 4 Technology Gaps
- Compact, Integrated Spectrometers for 100 to 1000 μm
- Optical-Blocking Filters
- Rapid Readout Electronics for X-Ray Detectors
- Short-Wave UV Coatings

### Tier 5 Technology Gaps
- Advancement of X-Ray Polarimeter Sensitivity
- Far-IR Spatio-Spectral Interferometry
- High-Precision Low-Frequency Radio Spectrometers and Interferometers
- Mid-IR Coronagraph Contrast
- Ultra-High-Resolution Focusing X-Ray Observatory Telescope
- Very-Wide-Field Focusing Instrument for Time-Domain X-Ray Astronomy

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**Technology Gap List to be updated by September 2021, responsive to Astro2020 recommendations**

-> See Joint PAG talk by Nick Siegler & Thai Pham  Friday Jan 8
Strategic Astrophysics Technology

Coronagraph masks/architectures

- Vortex Coronagraph (Serabyn/NASA-JPL)
- Phase Induced Amplitude Apodization Complex Mask Coronagraph (Belikov/NASA-ARC)
- Super-Lyot Coronagraph (Trauger/NASA-JPL)
- Apodized Pupil Lyot Coronagraph (Soummer/STScI)

Polarization and coronagraphy (Breckinridge/UA)

- Final report completed and posted

HiCAT testbed at STScI: Soummer SAT-2018
Wavefront-control Techniques

Single mode fiber and optimization for spectroscopy (Mawet/Caltech)
- Enables wide bandwidth at high contrast
- Next Step: demonstrate 20% bandwidth at $10^{-8}$ contrast in air

Mawet SAT-2018
Linear Dark Field Control Milestone

- Uses signal changes in bright region of coronagraph focal plane in a linear control loop that corrects speckles in the dark hole

- Milestone #1 achieved (pending ExoTAC review):
  - *Demonstration of the technique on an in-air testbed at NASA ARC (Currie et al 2020)*

- Next steps: demos in SCExAO, HCIT
Multi-Star Wavefront Control in Vacuum

- Demonstrated wavefront control in the vacuum testbed at JPL to create a dark hole at 50 $\lambda/D$ using diffraction orders of source.

- Next step: full multi-star (dark hole with two sources) in vacuum.

PI Rus Belikov (NASA/ARC)
Detectors and EPRV

Detectors
- Vis-band rad-hard photon-counting detectors (Rauscher/NASA-GSFC)
- Ultra-stable mid-IR detector array (Staguhn/JHU)

Extreme Precision Radial Velocity
- Micro-resonator optical etalon for radial velocity measurements (Leifer/NASA-JPL)

https://exoplanets.nasa.gov/exep/technology/TDEM-awards/
High Contrast Imaging Testbed Facility

Roman CGI

General Purpose Coronagraph Testbed

> DST2

Decadal Survey Testbed (DST)
MEMS Deformable Mirrors

- **50x50 Deformable Mirror demonstrations in vacuum**
  - MEMS DM narrowband demo in Decadal Survey Testbed contrast $8 \times 10^{-10}$ from 3.5 to 13.5 $\lambda/D$ narrowband at 516 nm; $2 \times 10^{-9}$ 10% band

- **Two 2000-actuator MEMS DM’s to undergo launch-level vibrations**
  - one not coated (to allow IR microscopy)
  - one coated

- **Next step: deliver DM units to JPL for pre-test performance characterization**
Deformable Mirror Survey

Goals:
1. Survey and document viable DM technologies across the world to inform future exoplanet space missions
2. Make recommendations for DM technologies
3. Identify new technologies that could be matured rapidly for flight

Status

- Evaluation criteria determined by a group of DM Subject Matter Experts
- Fact finding completed
  - 13 DM vendors from 6 different countries
- DM options have been scored relative to each other
  - Scores to be reviewed and concurred by SMEs
- Final report expected by 5/2021
Segmented Coronagraph Design & Analysis

Year-to-Date Accomplishments

- Incorporated quasi-static and dynamic telescope aberrations (by Ball Aerospace and Lockheed Martin) in simulations of contrast performance
- Produced coronagraph performance data for exoEarth yield computations

Next Steps:

- Understanding requirements on telescope dynamics to enable $10^{-10}$ coronagraph contrast performance
- Science yield analysis per coronagraph architecture
The Three Starshade Technology Gaps

(1) Starlight Suppression
Suppressing scattered light off petal edges from off-axis Sunlight (S-1)

(2) Formation Sensing
Sensing the lateral offset between the spacecraft (S-3)

(3) Deployment Accuracy and Shape Stability
Suppressing diffracted light from on-axis starlight and optical modeling (S-2)

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

Fabricating the petals to high accuracy (S-4)

https://exoplanets.nasa.gov/exep/technology/starshade/
Gap #1: Starlight Suppression and Edge Scatter

- **Subscale Starshade optical tests and model validation continues**
  - Tests of subscale starshades with deliberate shape errors show contrast changes in agreement with model predictions
  - See Harness et al. SPIE 2020 proceedings

- **Edge Scatter:**
  - Antireflection coating on starshade edge provides large margin on solar glint requirement

Fig 8: Before and after SAS measurements of a 50 cm AM edge segment which was coated with 450:800-2 at an angle of 45°. Also included in this plot is the representative uncoated coupon B27, as well as the coupon B33 which was coated in the same manner as the segment.
Gap #3: Shape Stability

- Starshade Petal System successfully demonstrated to maintain prelaunch shape within +/- 70 μm after deploy and thermal cycles
  - Modeling of results have been upgraded to include epoxy joints to achieve agreement with measurements
Starshade Technology Gaps Scorecard

(1) Starlight Suppression

Suppressing diffracted light from on-axis starlight and optical modeling (S-2)

Suppressing scattered light off petal edges from off-axis Sunlight (S-1)

(2) Formation Sensing

Sensing the lateral offset between the spacecraft (S-3)

(3) Deployment Accuracy and Shape Stability

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

Fabricating the petals to high accuracy (S-4)

https://exoplanets.nasa.gov/exep/technology/starshade/
Exoplanet Exploration Technology Colloquium Series

- Status of the Coronagraph Instrument (CGI) on the Roman Space Telescope, Feng Zhao (JPL)

- Status of MEMS Deformable Mirror Development in the HCIT, Eduardo Bendek and Garreth Ruane (JPL)

- Recordings and slides available:
  - https://exoplanets.nasa.gov/exep/technology/tech_colloquium/
Anticipating the Future…

• **Stellar Astrometry**
  – If Astro2020 recommends a direct imaging mission, will eventually need Earth-mass measurement capability that complements or is an alternative to EPRV.
  – Astrometry technology is already on the Technology Gap List but may add new, more focused Technology Gaps: for example, detector calibration, optical field distortion.

• **Nulling Interferometry**
  – Will include lessons learned since TPF-I from Keck, Palomar, LBT, and the VLT.
  – Identification of potential Technology Gaps to add to the gap list.
  – Astro2020 recommendations will set prioritization of this approach.
Starshade Technology Activity (S5) Technology Milestones Scorecard

**Starlight Suppression**
- Complete 2020: Contrast NB 1A, Contrast BB 1B, Modeling 2
- Complete 2023: Milestone Completed

**Scattered Sunlight**
- Edges 3

**Formation Flying**
- Sensing 4

**Shape Accuracy**
- Petal 5A, Truss Bay 7A, Inner Disk 7C
- Petal 5B, Truss Bay 7B, Inner Disk 7D

**Shape Stability**
- Petal 6A, Inner Disk 8A
- Petal 6B, Inner Disk 8B

by Phil Willems
Gap #3: Shape Stability

- Starshade petal thermal tests meet requirements
  - Bowing in the petal investigated; traced to thermal expansion of epoxy in the petal joints
Starlight Suppression and Edge Scatter

- Validate models of starshade performance
- Princeton testbed has been used to demonstrate starlight suppression to $< 10^{-10}$ over a 10% band of sub-scale starshade

- Last step: measure deliberately misshapen subscale starshades and compare with model predictions
Starlight Suppression and Edge Scatter

- Demonstrated starshade optical edge limits Solar scatter performance to lobe dimmer than mag 25 and maintains performance after thermal cycling
Technology Gap List

- **Astrophysics Technology Gap List**
  - Technology gaps for all three NASA Astrophysics Division (APD)’s programs
  - Database of technology activities:
    - [http://astrostrategictech.us/](http://astrostrategictech.us/)
  - Update coming in 2021, post-decadal

- **Exoplanet Technology Gap List**
  - Subset of APD gap list corresponding to exoplanet science:
    - [https://exoplanets.nasa.gov/exep/technology/gap-lists/](https://exoplanets.nasa.gov/exep/technology/gap-lists/)
V-NIR Coronagraph/Telescope Technology Gaps

Contrast
- CG-2: Coronagraph Architecture
- CG-3: Deformable Mirrors
- CG-4: Data Post-Processing
- CG-5: Wavefront Sensing and Control
- CG-6: Mirror Segment Phasing

Angular Resolution
- CG-1: Large Monolith Mirrors
- CG-1: Segmented Mirrors

Contrast Stability

Detection Sensitivity
- CG-7: Telescope Vibration Sensing and Control or Reduction
- Ultra-low Noise Visible (CG-8) and Infrared (CG-9) Detectors
Other Technology Gaps

UV Contrast

UV Detection Sensitivity

CG-12: Ultra-low Noise UV Detectors

Stellar Reflex Motion Sensitivity

Transit Spectroscopy Sensitivity

M-2: Laser Frequency Combs for Space-based EPRV

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

M-3: Astrometry

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

CG-10 UV/V/NIR Mirror Coatings
Mid-IR Technology Gaps

Mid-IR Coronagraph Contrast

CG-10 UV/V/NIR Mirror Coatings

Transit Spectroscopy Sensitivity

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