Recent Technology Activities

Technology Gaps

Strategic Astrophysics Technology (SAT) Grants

- Coronagraph architectures: modeling and demonstrations
- Wavefront control
- Extreme Precision Radial Velocity
- Detectors

Ultra-Stable Coronagraph Testbeds

Technosignatures Gap List Study

Starshade Technology Development

Segmented Coronagraph Design & Analysis Study
Astrophysics Technology Gaps

https://apd440.gsfc.nasa.gov/tech_gap_priorities.html

• A technology gap is the difference between a capability needed to enable a future mission and the current state-of-the-art

• The Astrophysics Division maintains a prioritized Technology Gap List

• Program Office technologists carry out a biennial Technology Gap List Process:
  – **Identify Technology Gaps** applicable to Astrophysics strategic objectives
  – **Rank Technology Gaps** to prioritize them for investment
  – **Inform the community** of NASA’s technology needs

• Published in the NASA Astrophysics Biennial Technology Report
# 2022 Astrophysics Technology Gaps

## Tier 1 Technology Gaps

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<th>Advanced Cryocoolers</th>
<th>Large Cryogenic Optics for the Mid IR to Far IR</th>
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<td>Large-Format, High-Resolution Focal Plane Arrays</td>
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<td>Coronagraph Stability</td>
<td>Large-Format, Low-Darkrate, High-Efficiency, Photon-Counting, Solar-blind, Far- and Near-UV Detectors</td>
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<td>Cryogenic Readouts for Large-Format Far-IR Detectors</td>
<td>Large-Format, Low-Noise and Ultralow-Noise Far-IR Direct Detectors</td>
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<td>Heterodyne Far-IR Detector Systems</td>
<td>Long-Wavelength-Blocking Filters for X-ray Micro-Calorimeters</td>
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<td>High-Performance, Sub-Kelvin Coolers</td>
<td>Low-Stress, High-Stability, X-ray Reflective Coatings</td>
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<td>High-Reflectivity Broadband Far-UV-to-Near-IR Mirror Coatings</td>
<td>Mirror Technologies for High Angular Resolution (UV/Vis/Near IR)</td>
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<td>High-Resolution, Large-Area, Lightweight X-ray Optics</td>
<td>Stellar Reflex Motion Sensitivity — Astrometry</td>
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<td>High-Throughput Bandpass Selection for UV/VIS</td>
<td>Stellar Reflex Motion Sensitivity — Extreme Precision Radial Velocity</td>
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<tr>
<td>High-Throughput, Large-Format Object Selection Technologies for Multi-Object and Integral Field Spectroscopy</td>
<td>Vis/Near-IR Detection Sensitivity</td>
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## Tier 2 Technology Gaps

| Broadband X-ray Detectors | Large-Format, High-Spectral-Resolution, Small-Pixel X-ray Focal-Plane Arrays |
| Compact, Integrated Spectrometers for 100 to 1000 μm | Polarization-Preserving Millimeter-Wave Optical Elements |
| Far-IR Imaging Interferometer for High-Resolution Spectroscopy | Precision Timing for Space-Based Astrophysics |
| Far-IR Spatio-Spectral Interferometry | Rapid Readout Electronics for X-ray Detectors |
| Fast, Low-Noise, Megapixel X-ray Imaging Arrays with Moderate Spectral Resolution | Starshade Deployment and Shape Stability |
| High-Efficiency X-ray Grating Arrays for High-Resolution Spectroscopy | Starshade Starlight Suppression and Model Validation |
| High-Resolution, Direct-Detection Spectrometers for Far-IR Wavelengths | UV Detection Sensitivity |
| Improving the Calibration of Far-IR Heterodyne Measurements | |
| Large-Aperture Deployable Antennas for Far-IR/THz/sub-mm Astronomy for Frequencies over 100 GHz |

## Tier 3 Technology Gaps

| Advancement of X-ray Polarimeter Sensitivity | High-Quantum-Efficiency, Solar-Blind, Broadband Near-UV Detector |
| Detection Stability in Mid-IR | Photon-Counting, Large-Format UV Detectors |
| Far-UV Imaging Bandpass Filters | Short-Wave UV Coatings |
| High-Efficiency Far-UV Mirror | Warm Readout Electronics for Large-Format Far-IR Detectors |
| High-Efficiency, Low-Scatter, High- and Low-Ruling-Density, High- and Low-Blazed-Angle UV Gratings |

## Tier 4 Technology Gaps

| Advanced Millimeter-Wave Focal-Plane Arrays for CMB Polarimetry | UV/Opt/Near-IR Tunable Narrow-Band Imaging Capability |
| Improving the Photometric and Spectro-Polarimetric Precision of Time-Domain and Time-Series Measurements | Very-Wide-Field Focusing Instrument for Time-Domain X-ray Astronomy |

## Tier 5 Technology Gaps

| Complex Ultra-Stable Structures for Future Gravitational-Wave Missions |
| Disturbance Reduction for Gravitational-Wave Missions |
| Gravitational Reference Sensor |
| High-Performance Spectral Dispersion Component/Device |
| High-Power, High-Stability Laser for Gravitational-Wave Missions |
| Laser Phase Measurement Chain for a Decihertz Gravitational-Wave Mission |
| Micro-Newton Thrusters for Gravitational Wave-Missions |
| Stable Telescopes for Gravitational Wave-Missions |
**Where to find the Gap List**

https://apd440.gsfc.nasa.gov/tech_gap_priorities.html

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### 2022 Astrophysics Strategic Technology Gaps

<table>
<thead>
<tr>
<th>Gap Name</th>
<th>Description</th>
<th>Current SOA</th>
<th>TRL</th>
<th>Performance Goals and Objectives</th>
<th>Scientific, Engineering and/or Programmatic Benefits</th>
<th>Applications and Potential Relevant Missions</th>
<th>Urgency</th>
</tr>
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<tbody>
<tr>
<td>Coronagraph Stability</td>
<td>The capability to maintain the deep starlight suppression provided by a coronagraph for a time period long enough to detect light from an exo-Earth.</td>
<td>RST CGI demonstrated $10^{-8}$ contrast in a simulated dynamic environment using LOWFS (which obtained 12 pm focus sensitivity)</td>
<td>3</td>
<td>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 sensor/control, metrology and correction of mirror segment phasing, vibration isolation/reduction. This stability is likely to require waveform error stability at the level of $10^{-10}$ pm per control step (of order 10 minutes).</td>
<td>This gap is likely to be closed by a combination of many factors in a coronagraph obsessive system, including active wavefront control at the coronagraph level, thermal control, active and passive ultra-stable structures, and disturbance isolation/reduction. Integrated modeling for traceability to flight environments is likely to be a key capability to close this gap.</td>
<td>IR/O/UV Great Observatory or any other coronagraph-based exoplanet direct-imaging mission.</td>
<td>Demonstration of feasibility and as much risk reduction as possible prior to mission formulation. TRL 6 in the mid-to-late 2020's.</td>
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</table>
Exoplanet Technology Gaps and Subgaps

https://exoplanets.nasa.gov/exep/technology/gap-lists/

- 10 Technology Gaps related to NASA's exoplanet science goals
  - Some gaps include subgaps:
    - Subgaps are missing capabilities that, if achieved, will partly or fully close the full gap.
    - Each subgap is associated with a higher-level gap, and includes additional details.

<table>
<thead>
<tr>
<th>Technology Gap and Description</th>
<th>Current State-of-the-Art</th>
<th>Performance Goals and Objectives</th>
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<tr>
<td><strong>Mirror Technologies for High Angular Resolution (UV/Vis/NIR)</strong></td>
<td>Monolith: 3.5-m sintered SiC with &lt; 3 μm SFE (Herschel); 2.4-m ULE with ~10 nm SFE (HST); Waterjet cutting is TRL 9 to 14&quot; depth, but TRL 3 to &gt;18&quot; depth. Fused core is TRL 3; slumped fused core is TRL 3 (AMTD); 4-m class Zerodur mirrors from single boules are TRL 4. Segmented: (no flight SOA): 6.5 m Be with 25 nm SFE (JWST); Non-NASA: 6 DOF, 1-m class SiC and ULE, &lt; 20 nm SFE, and &lt; 5 nm wavefront stability over 4 hr with thermal control</td>
<td>Large (4–18 m) monolith and multi-segmented mirrors for space that meet SFE &lt; 10 nm rms (wavelength coverage 400–2500 nm); Wavefront stability better than 10 pm rms per wavefront control time step; CTE uniformity characterized at the ppb level for a large monolith; Segmented apertures leverage 6 DOF or higher control authority meter-class segments for wavefront control.</td>
</tr>
<tr>
<td><strong>Coronagraph Contrast and Efficiency</strong></td>
<td>unobscured pupil: 4×10^{-10} raw contrast at 10% bandwidth, angles of 3-15 μD (Lyot coronagraph demo in HICAT); obscured pupil: 1.8×10^{-9} raw contrast at 10% bandwidth across angles of 3-9 μD (Roman CGI Lab Demos); segmented/unobscured pupil: 2.5×10^{-8} raw contrast in monochromatic light across 6-10 μD (Lyot coronagraph demo in HiCAT)</td>
<td>Maximized science yield in imaging and spectroscopy for a direct imaging telescope/mission. ≤ 10^{-10} raw contrast, &gt;10% throughput; inner working angle ≤ 3 μD, outer working angle ≥ 45 μD [TBD], 20% bandwidth; unobscured/segmented pupil</td>
</tr>
</tbody>
</table>

For the two distinct cases of monolith and segmented primary mirrors, Sub-gaps that could partially or fully close this gap:
- Mirror Substrate and Structure
- Mirror Positioning Actuators
- Gravity Sag Offloader
- Coefficient of Thermal Expansion Characterization
- Mirror Finishing
- UV Coatings: Wavefront Effects

Click here for a PDF with all exoplanet technology gaps and subgaps
V-NIR Coronagraph/Telescope Technology Gaps

Coronagraph Contrast and Efficiency
- Coronagraph Architectures
- Deformable Mirrors
- Coronagraph Efficiency
- Computational Throughput in Space
- High Bandwidth Optical Comm
- Autonomous On-board WFSC Architectures

Mirror Technologies for High Angular Resolution
- Mirror Substrate and Structures
- Mirror Finishing
- Mirror Positioning Actuators
- Gravity Sag Offload
- CTE Characterization
- UV Coatings: Wavefront Effects

Coronagraph Stability
- Wavefront Sense/control
- Precision Pointing Stability
- Disturbance Reduction and Observatory Stability
- Segment Relative Pose Sense/Control
- Telescope Thermal Sense/Control
- Vibration Isolation
- Laser Gauges
- Integrated Modeling of Coronagraph/Telescope System

Vis/NIR Detection Sensitivity
- NIR Detectors
- UV/Vis Detectors
- Photon-counting energy-resolving detectors
Starshade Technology Gaps

Starlight Suppression and Model Validation

- Suppressing scattered light off petal edges from off-axis sunlight

Deployment Accuracy and Shape Stability

- Suppressing diffracted light from on-axis starlight and optical modeling
- Positioning the petals to high accuracy, blocking on-axis starlight, maintaining overall shape on a highly stable structure

Formation Sensing

- Fabricating the petals to high accuracy
- Sensing the lateral offset
Other Technology Gaps

Stellar Reflex Motion Sensitivity: Astrometry

UV Detection Sensitivity

Stellar Reflex Motion Sensitivity: Extreme Precision Radial Velocity
- Detectors for High-res Spectrographs
- Dispersive Optics
- Advanced Photonics
- Ground-based Visible-light Adaptive Optics
- Precision Calibration

Detection Stability (Mid-IR)

Ultra-low Noise UV Detectors

Ultra-stable Mid-IR Detectors for Transit Spectroscopy
10 Currently Active Strategic Astrophysics Technology (SAT) Awards

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)

Wavefront-control techniques
- Single mode fiber and optimization for spectroscopy (Mawet/Caltech)
- Linear Dark Field Control (Guyon/Arizona)
- Multi-star Wavefront Control (Belikov/NASA-ARC)

Ultra-low Noise 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 (Vasisht/NASA-JPL)
Newly Selected SAT-2021 Awards

• **Dual-Purpose coronagraph masks for enabling high-contrast imaging with an IR/O/UV flagship mission**
  PI J. Kent Wallace (JPL)
  – Aims to monitor wavefront errors in a coronagraph using a Zernike wavefront sensor and out-of-band light, and to actively correct the errors.

• **Adaptive High-order Wavefront Control Algorithms for High-contrast Imaging on the Decadal Survey Testbed**
  PI Kerri Cahoy (MIT)
  – Will demonstrate methods to maintain a coronagraph dark hole using focal plane data

• **Next call issued in ROSES-2022 with TBD due dates, likely to be due Dec 2022**
SAT Coronagraph Demonstrations in the High-Contrast Imaging Testbed

• **Vortex coronagraph (PI Serabyn)**
  – Vortex coronagraph was LUVOIR-B and HabEx baseline
  – Achieved a new contrast record for the vector vortex at 10% bandwidth between 3-9 $\lambda/D$ of $1.5 \times 10^{-9}$. 
  – See papers at upcoming July SPIE meeting

• **Super Lyot ExoEarth Coronagraph (PI Trauger)**
  – Hybrid Lyot coronagraph has demonstrated the deepest contrast to-date
  – Replicated contrast performance with simple Lyot coronagraph at $3.4 \times 10^{-10}$ at 10% band 3-9 $\lambda/D$ 360-degree dark hole
  – Results coming soon with next generation masks

• **Next in testbed:**
  – Multi-star wavefront control demonstrations (PI Belikov)
  – High-bandwidth coronagraph demonstrations (PI Mawet)
Other Recent SAT Highlights

• **Environmental Tests of MEMS Deformable Mirrors (PI Bierden)**
  – Final Report completed and available on ExEP website
  – performed random vibration testing on an earlier generation of MEMS deformable mirrors, showing they survived launch loads.

• **Linear Dark Field Control (PI Guyon)**
  – Uses residual starlight outside coronagraph dark hole to stabilize the dark hole, potentially leading to looser telescope stability requirements
  – Milestone Whitepaper approved for tests in vacuum at higher contrast and using spectral information and posted on ExEP website
  – Technique will be tested at high contrast in HCIT using spectral information in the coming months

• **Astrometry Bench installed in vacuum chamber (PI Bendek)**
  – APRA-funded demonstration of diffractive pupil technology in vacuum
Testbed Infrastructure

- **Decadal Survey Testbed 2**
  - New ultrastable coronagraph testbed bench with additional pupil plane
  - Achieved first light in November 2021
  - Installation planned for mid-July
  - Available to future investigators ~ next FY
ExEP-Contributed Masks for Roman Space Telescope Coronagraph Instrument (CGI)

- CGI currently in flight build: all coronagraph masks have been fabricated including ExEP contributions:
  - Zernike Wavefront Sensor (ZWFS) dimple masks:
    - 23 mm dia
    - 25 um dimples
  - Multi-star Wavefront Control mask:
Segmented Coronagraph Design & Analysis Study

- Multi-institutional study of end-to-end modeling of telescope dynamics, wavefront control, and coronagraph → science yield

- Studies Currently Underway
  - End-to-end modeling of a LUVOIR-B-like telescope dynamics, wavefront control, and coronagraph → exo-Earth yield (in collaboration with Lockheed Martin)
  - Effect of polarization aberration on exo-Earth yield
  - Effect of segment-edge roll-off on exo-Earth yield

The 3 most dominant modes in dynamical wavefront variance of the modeled telescope structure. Effects of vertical hinges in the primary mirror’s backplane support are evident. [Credits: L. Dewell (Lockheed Martin), R. Juanola-Parramon (NASA GSFC)]
Starshade Technology Development

- Since 2016, Starshade Technology Activity has overseen technology development, achieving a series of milestones that worked towards closing the starshade technology gaps
  - https://exoplanets.nasa.gov/exep/technology/starshade/

- Starshade technology development will transition from directed funding to a competed funding model

- Remaining work to TRL 5:
  - Complete analysis of subscale demos and model validation
  - Further demonstrations of deployment and shape stability at higher levels of integration
## Starshade Scorecard

### Formation Flying
- **Complete pre-Astro2020**
  - Starlight Suppression
    - Contrast NB 1A
    - Contrast BB 1B
    - Modeling 2
  - Scattered Sunlight
    - Edges 3
  - Sensing 4

### Critical Features
- **Complete post-Astro2020**
  - Milestone Completed
  - Report under Review
  - In Progress

### Shape Accuracy
- **Complete pre-Astro2020**
  - Petal 5A
  - Truss Bay 7A
  - Inner Disk 7C

### Shape Stability
- **Complete post-Astro2020**
  - Petal 5B
  - Truss Bay 7B
  - Inner Disk 7D

### All Features
- Petal 6A
- Inner Disk 8A
- Inner Disk 8B
The ExEP commenced a fact-finding study to understand where it can make a positive impact towards the search for technological life.

The Study will help the ExEP better understand the landscape and needs of the field if investments are ever considered again (Congress, donors).

Key fields within the database will include:
- Technosignature search approaches
- Technology needs and gaps
- Other needs to advance the searches (access to existing facilities, future facilities, AI/ML, $’s, data archiving)

Study is planned to conclude in CY22
- Second milestone completed this month (search approaches)
- Reviewed by an external Technosignatures Assessment Committee
Exoplanet Exploration Technology Colloquium Series

- Choosing the Future: Kepner-Tregoe Matrix for Complex Trades
  Gary Blackwood (JPL)

- Coming soon: TRL assessment, coronagraph stability studies.
- Recordings and slides available:
  - https://exoplanets.nasa.gov/exep/technology/tech_colloquium/
Join our Sunday morning session for more details on Precursor science, the Science Evaluation Team, the Technology Strategy Team and how you, the ExoPAG can be involved.
BACKUP