Exoplanet Exploration Program Technology

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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

Nulling Interferometry Study

Technosignatures Gap List Study

Starshade Technology Development

Segmented Coronagraph Design & Analysis Study

Roman/CGI
The Future is Here!

Astrophysics
Decadal Survey Missions

1972 Decadal Survey
Hubble

1982 Decadal Survey
Spitzer

1991 Decadal Survey
Webb

2001 Decadal Survey
Webb

Pathways to Discovery in Astronomy and Astrophysics for the 2020s
Key Exoplanet Decadal Recommendations

Introducing the Maturation Program:

Recommendation: The NASA Astrophysics Division should establish a Great Observatories Mission and Technology Maturation Program, the purpose of which is to co-develop the science, mission architecture, and technologies for NASA large strategic missions identified as high priority by decadal surveys.

An IR/O/UV Great Observatory focused on exoplanet science is first:

Recommendation: After a successful mission and technology maturation program, NASA should embark on a program to realize a mission to search for biosignatures from a robust number of about ~ 25 habitable zone planets and to be a transformative facility for general astrophysics. If mission and technology maturation are successful, as determined by an independent review, implementation should start in the latter part of the decade, with a target launch in the first half of the 2040s.
NASA’s response to the Decadal
See Paul Hertz town hall from Jan 11, 2022

• **Future Great Observatory preparation in pre-Phase A stages:**
  – Stage 1 is now; includes precursor science and technology work
  – Stage 2 starts in a few years; begins the Maturation Program and will add an Analysis of Alternatives and science / technology / architecture trades
  – Stage 3 includes the decision to start and a transition to the classic pre-Phase-A

• **APD is defining what technology development means under the Maturation Program**
  – How to best use SATs and other funding mechanisms to advance technology
  – How to engage industry
  – Understanding the future of large launch vehicles
  – Considering servicing of future large missions
  – Exploring international collaborations
Astrophysics Technology Gaps

• 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 Selection and Prioritization 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

• The last update was in 2019
# 2019 Astrophysics 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 Ultra-Low-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 LUVIOIR
- 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
Astrophysics Technology Gaps

- Inputs from the community were due Jan 3, 2022

- 96 gap submissions received
  - 48 gaps currently on the gap list

- Next Steps:
  - Each gap assigned to one of the 3 program offices: PCOS, COR, ExEP
  - Disposition, review and consolidate gaps
  - Prioritize gaps
  - Work reviewed by ExoTAC

- Delivery of Gap List to community in April 2022
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)

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)
SAT coronagraph demonstrations in the High-Contrast Imaging Testbed

• **PIAACMC (PI Belikov)**
  – PIAACMC technology promises excellent inner working angle
  – Achieved $1.5 \times 10^{-8}$ contrast with a segmented pupil, target was $10^{-9}$
  – Error budgeting for Final Report coming soon

• **Vortex coronagraph (PI Serabyn)**
  – Vortex coronagraph was LUVOIR-B and HabEx baseline
  – New record contrast achieved $2 \times 10^{-9}$ over 10% band for working angles 3-10 $\lambda/D$
  – Record for 20% band: $6 \times 10^{-9}$ contrast over 3-10 $\lambda/D$
  – Earlier in the summer: $5 \times 10^{-9}$ contrast over 10% band achieved with a static segmented pupil

• **Super Lyot ExoEarth Coronagraph (PI Trauger)**
  – Hybrid Lyot coronagraph has demonstrated the deepest contrast to-date
  – Installed in testbed and next in queue; results coming soon.
Other Recent SAT Highlights

• **Multi-star wavefront control (PI Belikov)**
  - Enables coronagraph to observe planets in multi-star systems
  - Installed in vacuum testbed; demonstrations commencing soon
  - Contributed mask for Roman CGI fabricated (Eduardo Bendek; technical lead)

• **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 report published on ExEP website
  - Spatial dark field control technique demonstrated a factor 30 improvement in coronagraph contrast at $10^{-6}$ on an in-air testbed
  - Future milestones include tests in vacuum at higher contrast and using spectral information
Testbed Infrastructure

- **Decadal Survey Testbed 2**
  - New ultrastable coronagraph testbed bench with additional pupil plane
  - Achieved first light in November 2021
  - Will be available to future investigators starting with SAT-2021

- **MEMS 2K DM environmental tests**
  - The Boston Micromachines 2k MEMS deformable mirrors (DMs) were subjected to 3-axes random vibe with Roman Space Telescope launch loads.
  - Passed both functional and coronagraph performance testing and achieved better than $10^{-8}$ contrast in the HCIT's In-Air Coronagraph Testbed.
  - A final report has been completed.

- **A new DM electronics controller under development by Teilsch**
  - 18 bit control, more compact design
Segmented Coronagraph Design & Analysis Study

- **Purpose:**
  - Coronagraph feasibility with segmented-mirror telescope
  - Coronagraph/segmented telescope system feasibility

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

- **In collaboration with Ball, Lockheed Martin telescope modeling and in coordination with STScI wavefront-control modeling (for LUVOIR-A)**
  - Reconfirmed requirement for ~10 pm WFE stability, per LUVOIR report

**Possible Next Steps:**
- Study ~ 6-meter-class telescope yield sensitivities
- Telescope model to incorporate active metrology
- Enhance model integration, fidelity, and access
S5: Closing Starshade Technology Gaps

https://exoplanets.nasa.gov/exep/technology/starshade/

(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
Fabricating the petals to high accuracy (S-4)

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

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

• **Model validation**
  - Traces subscale demo performance to full-scale starshade
  - Including vector diffraction still in progress; agreement not quite at the 25% level.

• **Formation Flying:**
  - Starshade needs sensing of line of sight position relative to telescope to within centimeters with separations of ~10,000 km
  - Princeton subscale testbed demonstration of high contrast with simultaneous position sensing in the loop (PI Kasdin)
  - Final Report on this technique passed review by ExoTAC, is posted on ExEP website

• **Petal Shape Stability**
  - Starshade must maintain shape in operational thermal environment
  - Milestone final report on thermal deformation of petals completed and posted on website
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 summer of CY22
- First milestone completed in December 2021 (data fields to be collected)
- Reviewed by an external Technosignatures Assessment Committee
Completed Nulling Interferometry Study

• In 2021, ExEP completed a study to update technology gaps related to nulling interferometry

• JPL-GSFC Team: B. Mennesson (PI), G. Serabyn, S. Martin, W. Danchi, C. Stark, P. Chen
  – Revisited TPF-I science goals
  – Summarized lessons learned since TPF-I
  – Preliminarily investigated application of high spectral resolution
  – Identified technology gaps

• 2021 Decadal Survey did not prioritize this capability

The Gap List

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Exoplanet Exploration Technology Colloquium Series

- A Worldwide Survey of Deformable Mirrors
  Eduardo Bendek (JPL)

Recordings and slides available:
  - https://exoplanets.nasa.gov/exep/technology/tech_colloquium/

![Diagram showing worldwide survey of deformable mirrors]
Exoplanet Missions

The path towards the Future Great Observatories is under development

Join us!
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
**Other Technology Gaps**

**UV Contrast**
- CG-10 UV/V/NIR Mirror Coatings

**UV Detection Sensitivity**
- CG-12: Ultra-low Noise UV Detectors

**Stellar Reflex Motion Sensitivity**
- M-1: Ground-based Ultra-high Precision Radial Velocity
- M-2: Laser Frequency Combs for Space-based EPRV
- M-3: Astrometry
- M-4: Ultra-stable Mid-IR Detectors for Transit Spectroscopy

**Transit Spectroscopy Sensitivity**
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