What’s New in Exoplanet Technology?

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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.

Contrast vs Separation
Figure from 2013

Plot from Peter Lawson 2013; blue curves were early predictions added later.
**Coronagraph State-of-the-Art in 2009**

**Lab Demonstrations**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Hybrid Lyot (linear mask)</th>
<th>PIAA</th>
<th>Vortex</th>
<th>Visible Nuller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw contrast (at IWA)</td>
<td>1.2 x 10^{-10}</td>
<td>2 x 10^{-7}</td>
<td>10^{-8}</td>
<td>10^{-8}</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>2%</td>
<td>mono</td>
<td>mono</td>
<td>10nm/630nm</td>
</tr>
<tr>
<td>Working Angle</td>
<td>4 - 10 $\lambda$/D</td>
<td>1.65 - 4.4 $\lambda$/D</td>
<td>2.5 – 12 $\lambda$/D</td>
<td>2 – 4 $\lambda$/D</td>
</tr>
</tbody>
</table>

Reference:
- TDEM-09 whitepaper (Guyon)
- TDEM-10 whitepaper (Serabyn)
## 2010 Decadal Survey Recommendations

... and NASA Response

<table>
<thead>
<tr>
<th>Decadal Survey Recommendation</th>
<th>NASA Actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large-scale 1. WFIRST</td>
<td>In Phase A, launch in mid-2020s (see Section 4)</td>
</tr>
<tr>
<td>Large-Scale 2. Augmentation to Explorer Program</td>
<td>Executing 4 Announcements of Opportunity (AOs) per decade (see Section 5)</td>
</tr>
<tr>
<td>Large-Scale 3. LISA</td>
<td>Partnering on ESA’s space-based gravitational wave observatory (see Section 6.1)</td>
</tr>
<tr>
<td>Large-Scale 4. IXO</td>
<td>Partnering on ESA’s Athena X-ray observatory (see Section 6.2)</td>
</tr>
<tr>
<td>Medium-Scale 1. New Worlds Technology Development Program</td>
<td>WFIRST coronograph; starshade and coronagraph technology development; Doppler spectrograph on W1YN telescope; exozodiacal dust survey with LBTI (see Section 7.1)</td>
</tr>
<tr>
<td>Medium-Scale 2. Inflation Probe Technology Development Program</td>
<td>Multiple balloon-borne investigations plus SAT investments (see Section 7.2)</td>
</tr>
<tr>
<td>Small-Scale. Research Program Augmentations</td>
<td>R&amp;A as of FY2016 up 20% from FY2010; increase not targeted except TCAN (see Section 7.3)</td>
</tr>
<tr>
<td>Small-Scale. Intermediate Technology Development Augmentation</td>
<td>Initiated Strategic Astrophysics Technology program; focused on identified strategic missions</td>
</tr>
<tr>
<td>Small-Scale. SPICA (U.S. contribution)</td>
<td>Not supported as a strategic contribution; candidate for Explorer Mission of Opportunity</td>
</tr>
</tbody>
</table>

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.
2010 Decadal Survey Recommendation
Medium Scale Category

“...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.”
Cumulative Number of Detections

- Radial Velocity
- Transits
- Microlensing
- Imaging
- Timing Variations
- Orbital Brightness
- Modulation
- Astrometry

Discovery Year

3778 (as of 9/7/18)
We now know that in our Galaxy…

Planets are common (> 1 per star)

Planets with sizes 0.5-2 times Earth are the most common

Earth-size planets in the Habitable Zone are common

…we’re ready for the search for life
Potential Biosignature Gases

Spectral Lines

Robinson 2016
External Occulters (Starshades)

Nulling Interferometry

Internal Occulters (Coronagraphs)
Targeted technology grants

- 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.

- About 40 awards since 2010 have advanced the technology readiness of starshades, coronagraphs, and their associated supporting technologies.
High Contrast Imaging Testbed Facility (JPL)
Coronagraph technology advancement

HCIT-1

HCIT-2
Coronagraph Progress for Space
Contrast vs. Bandwidth

Vector Vortex
2.4-9 $\lambda$/d

Visible Nulling
1.5-2.5 $\lambda$/d

PIAA
2.5-5 $\lambda$/d

Shaped Pupil
4.5-14 $\lambda$/d

Vector Vortex 2013
3-8 $\lambda$/d

Hybrid Lyot
4.5-14 $\lambda$/d

Contrast (Background/Source)

Optical Bandwidth (percent)
Coronagraph Progress for Space

• In 2013, coronagraphy was “spun off” from the ExEP to the WFIRST project to support technology advancement for their coronagraph instrument.

• Achieved TRL 5 in 2017

• Advancing component technologies
  – Deformable mirrors
  – Ultar-low noise detectors (EMCCDs)
  – Low-order wavefront sensors
  – Post-processing
Starshade Progress

• Starshade advanced through TDEM Program:
  – petal manufacturing
  – optical demonstrations
  – inner disk deployment

• In 2016, the starshade was spun off to establish a starshade technology development activity.
Petal Unfurler Testbed 2.0
JPL plus Tendeg Gravity Offloader
Inner Disk Deployment
10 m Prototype Demonstration (JPL)
Optical Shield Deployment

5 m Prototype Demonstration
Still a Way to go to Directly Imaging Exo-Earths

We are here now
WFIRST will get us here
Needed for exo-Earth study
Active TDEMS

• **Advancing Coronagraphy to < 10^{-9}**
  – Vortex (PI Gene Serabyn/JPL)
  – Hybrid Lyot (PI John Trauger/JPL)
  – PIAA (PI Rus Belikov/ARC)
  – APLC (PI Remi Soummer/STScI)
  – Multi-star wavefront control (PI Rus Belikov/ARC)

• **Understanding and Minimizing the Effects of Polarization**
  – Jim Breckinridge (Caltech) and UA team performing independent polarization ray-trace of the HabEx and LUVOIR optics

• **Advancing a Second 10^{-10} Deformable Mirror**
  – MEMS 32x32 (PI Paul Bierden/Boston Mocromachines)
  – MEMS 50x50 (SBIR)
Segmented Mirror Technology Program

• Telescope apertures will continue to get larger and structural and wavefront error stability will be challenging when working with coronagraphs.

• Industry awards created to address system-level design and modeling challenges for achieving picometer-level wavefront error stability in a segmented UV/V/NIR space telescope.

Ultra-Stable Large Telescope Research and Analysis (ULTRA), PI Scott Knight (Ball Aerospace)

System-Level Segmented Telescope Design, PI Larry Dewell (Lockheed Martin)
Segmented Coronagraph Design and Analysis

• Purpose: Ensure there is at least one coronagraph architecture that can meet the contrast requirements of future large segmented space telescopes to directly image and characterize exo-Earths.

• Promising designs delivered of the APLC (STScI/GSFC) and Vortex (Caltech/JPL) teams; HLC (JPL) catching up, PIAACMC (UA/Ames) and VNC GSFC) struggling to meet metrics.

• Lessons learned:
  – Big dropoff in throughput seen when secondary obscuration exceeds 30% of the primary mirror diameter
  – Angular size of the star problematic for some coronagraphs
  – Segmentation gaps are not a major problem (if small)
  – Central obscuration biggest challenge

• Next steps
  – Test new apodization masks in testbeds (not yet vacuum)
  – Test the robustness of the designs to wavefront errors and tolerancing: Do these coronagraphs put constraints on the telescopes that are unrealistic?
Decadal Survey Testbed
Advancing the next generation of coronagraphs

• **Purpose:**
  – Develop a testbed that is sufficiently low noise to demonstrate next-generation coronagraphs reach $10^{-10}$ contrast
  – To be made available to community

• **Currently Commissioning with a clear aperture plus Hybrid Lyot**
  – Plan is to reach a new contrast record by the end of this CY ($\leq 10^{-10}$)

• In CY19, add a segmented/obscured mask to simulate the segmentation pattern of a large space telescope mirror
Starshade Deployment Trade Study Completed
Wrapped petal architecture selected

- Technology Development Plan advanced to bring the starshade to TRL 5 by early 2020s.
  - Review of milestones by ExoTAC in August
  - Delivery of Plan for NASA HQ approval in September
Inputs to National Academies Exoplanet and Astrobiology Strategy Committees


- Briefed the NAS Exoplanet Science Strategy committee at their Irvine meeting on April 20, 2018 on “Exoplanet Technology Gaps” [https://exoplanets.nasa.gov/internal_resources/893/](https://exoplanets.nasa.gov/internal_resources/893/)
in-Space Assembled Telescope (iSAT) Study

• Chartered by NASA SMD and APD to answer the question:

  *When is it worth assembling telescopes in space rather than building them on the Earth and deploying them autonomously from individual launch vehicles?*

• Final deliverable is a White Paper to the Decadal Survey Committee in Spring 2019

• **Activity 1a: Modularizing a 20 m space telescope**
  – Workshop held at Caltech June 5-7

• **Activity 1b: Assembling and testing the 20 m modularized telescope in space**
  – Robotics, orbit, launch vehicle, assembly platform
  – Workshop scheduled for October 2-4 at LaRC
# 2018 ExEP Prioritized Technology List

<table>
<thead>
<tr>
<th>Tech. ID</th>
<th>Technology Title</th>
<th>Impact</th>
<th>Urgency</th>
<th>Trend</th>
<th>2018 Score</th>
<th>2017 Score</th>
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<tbody>
<tr>
<td>CG-2</td>
<td>Coronagraph Architecture</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>90</td>
<td>85</td>
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<td>S-2</td>
<td>Starlight Suppression and Model Validation</td>
<td>4</td>
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<td>Controlling Scattered Sunlight</td>
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<td>Lateral Formation Sensing</td>
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<td>S-5</td>
<td>Petal Positioning Accuracy and Opaque Structure</td>
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<td>S-4</td>
<td>Petal Shape and Stability</td>
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<td>CG-3</td>
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<td>Telescope Vibration Sense/Control or Reduction</td>
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<td>Ultra-Low Noise Near-Infrared Detectors</td>
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<td>Wavefront Sensing and Control</td>
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<td>CG-4</td>
<td>Data Post-Processing Algorithms and Techniques</td>
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<td>CG-10</td>
<td>Mirror Coatings for UV/NIR/Vis</td>
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<td>M-2</td>
<td>Space-based Laser Frequency Combs</td>
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<td>CG-13</td>
<td>Ultra Low-noise Mid-IR detectors</td>
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<td>M-1</td>
<td>Extreme Precision Ground-based Radial Velocity</td>
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<td>75</td>
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<td>CG-14</td>
<td>Mid-IR Large Aperture Telescopes</td>
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<td>CG-15</td>
<td>Mid-IR Coronagraph Optics and Architecture</td>
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<td>CG-16</td>
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<td>Ultra-Low Noise UV Detectors</td>
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<td>60</td>
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</tr>
</tbody>
</table>

**Coronographs and Starshades**

**Mass measurement to be advanced?**

**Mid-IR interferometry technology next decade?**