Mirror Technology Days Workshop
Greenbelt, MD, November 2016

Technology Needs for the Exoplanet Exploration Program

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August 24, 2016: Using a telescope in Chile, European astronomers detect a planet around Proxima Centauri, only 4.2 light years away.
3,402 Confirmed Exoplanets
(as of 10/31/16)

Number of Planets

Discovery Year

Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness
Modulation
Astrometry

http://exoplanetarchive.ipac.caltech.edu/exoplanetplots/
<table>
<thead>
<tr>
<th>Method</th>
<th>Percentage</th>
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<tbody>
<tr>
<td>Transit</td>
<td>78.9%</td>
</tr>
<tr>
<td>Radial Velocity</td>
<td>17.6%</td>
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<tr>
<td>Imaging</td>
<td>1.3%</td>
</tr>
<tr>
<td>Microlensing</td>
<td>1.2%</td>
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</table>

0.44% Transit Timing Variations, 0.24% Eclipse Timing Variations, 0.18% Orbital Brightness Modulation, 0.15% Pulsar Timing, 0.06% Pulsation Timing Variations, 0.03% Astrometry
Starlight Suppression is the Key Technology in the Search for Life on Earth-Size Exoplanets
Starlight Suppression Technologies

External Occulters (Starshades)

Nulling Interferometry

Internal Occulters (Coronagraphs)
Exoplanet Missions

Driving science is direct imaging of exo-Earths

Proposed Pre-2020 Decadal Mission Concept Studies
- Orgins Space Telescope (FAR IR Surveyor)
- Habitable Exoplanet Imaging Mission
- Large UV/Optical/IR Surveyor
- X-ray Surveyor

1 NASA/ESA Partnership
2 NASA/ESA/CSA Partnership
3 CNES/ESA
Towards the Detection of Exo-Earths

We are currently here

Contrast Ratio (planet/star)

Angular Separation (arcsec)

Need for Earth Study

Contrasts achieved after post-processing

Solar system planets shown at 10 pc

Contrast Ratio (planet/star)

Angular Separation (arcsec)

WFIRST will take us here: $3 \times 10^{-9}$
Possible New Worlds Exoplanet Telescopes (mid-2030s)

- Large Ultra-Violet Optical Infrared Telescope (LUVOIR)
- Habitable Exoplanet Imaging Mission (Hab-Ex)
- Coronagraph
- Starshade
Two direct imaging mission concept studies: HabEx and LUVOIR

- Both have goal of studying Earth-like planets in reflected light; they differ in levels of ambition
  - HabEx to “search for” signs of habitability and biosignatures
  - LUVOIR to “constrain the frequency of habitability and biosignatures” = larger statistical survey of exo-Earths, larger aperture

- Different priorities
  - HabEx to focus on exoplanets; “best effort” only on general astrophysics. Aperture < 8 m. Study led by NASA JPL.
  - LUVOIR gives equal priority to exoplanets and general astrophysics. Aperture 8-16 m. Study led by NASA Goddard.

- They are likely to differ in cost and technical readiness

- Interim reports late 2017; final reports early 2019
NASA Exoplanet Exploration Program

One of three programs within the NASA Astrophysics Division, Science Mission Directorate

Purpose described in 2014 NASA Science Plan

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

http://exoplanets.nasa.gov/exep
The NASA Exoplanet Exploration Program

Space Missions and Mission Studies
- Kepler, K2
- WFIRST
- Probe-Scale: Starshade

Supporting Research & Technology
- Key Sustaining Research
  - Large Binocular Telescope Interferometer
  - Keck Single Aperture Imaging and RV
  - Extreme Precision Doppler Spectrometer
- Technology Development
  - Coronagraphs
  - Starshades

Public Engagement
- NASA Exoplanet Science Institute
- Extreme Precision Doppler Spectrometer
- Coronagraphs
- Starshades
- WFIRST Coronagraph
- Starshade
- Kepler, K2
21 New Technology Gaps from Exoplanet Community

14 Technology gaps carried over from 2016

Selection: enables or enhances direct detection and characterization of exoplanets?

Yes

Prioritize technologies according to criteria (Impact, Urgency, and Trend)

ExEP Technology Gap List

Neither enhancing nor enabling

No, but could benefit exoplanet science

List of technologies that benefit exoplanet science, aka “Watch List”

Reviewed by Exo-TAC
## 2017 ExEP Technology Gap List

<table>
<thead>
<tr>
<th>Gap ID</th>
<th>Gap Title</th>
<th>Impact</th>
<th>Urgency</th>
<th>Trend</th>
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<td>S-2</td>
<td>Optical Performance Demonstration and Optical Modeling</td>
<td>4</td>
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<td>CG-1</td>
<td>Large Aperture Mirrors</td>
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<td>Coronagraph Architecture</td>
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<td>Mirror Figure (Segment Phasing) Sense &amp; Control</td>
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<td>NIR Ultra-Low Noise Detector</td>
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<td>Control Edge-Scattered Sunlight</td>
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<td>Lateral Formation Flying Sensing</td>
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<td>S-5</td>
<td>Inner Disk Deployment</td>
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<td>Low-Order Wavefront Sensing and Control</td>
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<td>Extreme Precision Radial Velocity</td>
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<td>Post-Data Processing</td>
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<td>UV/NIR/Vis mirror coatings</td>
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<td>3</td>
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</table>

**Enabling Gap**
- Sub-Kelvin Coolers
- Advanced Cryocooler
- Mid-IR Ultra-low Noise Detector

**Enhancing Gap**
- Astrometry

**Watch List**
- Will be posted to website later this month
Coronagraph/Telescope Technology Needs

Starlight Suppression (Contrast)

Angular Resolution

Contrast Stability

Detection Sensitivity
Coronagraphy Optics and Architectures

**Future Needs:**
- Raw contrast $< 10^{-9}$ (obscured and segmented)
- IWA $\leq 3 \lambda / D$
- Bandwidth $\geq 10\%$
- Throughput $\geq 10\%$

**SOA:**
- WFIRST: few x $10^{-9}$ (obscured; raw contrast)
- Lab: $6 \times 10^{-10}$ (unobscured; Hybrid Lyot)
- IWA $\sim 3 \lambda / D$
- Bandwidth 10\%

**Current Activities:**
- WFIRST coronagraphs planned to achieve TRL 5 by end FY16; NASA review on 11/8/16
- Additional demonstrations ongoing at STScI (APLC), Vortex (Caltech), and GSFC (VNC)
- ExEP design study to identify coronagraph architectures that can reach $< 10^{-9}$ on large **segmented** apertures (FY16-17)
- HCIT prepping for a 1e-10 contrast testbed
- Polarization assessments of HabEx/LUVOIR (FY17)
Segmented Coronagraph Design and Analysis
(funded by the ExEP; led by S. Shaklan/JPL)

**Coronagraph Designs**

1. Apodized Pupil Lyot Coronagraph (STScI)
2. Vortex Coronagraph (Caltech)
3. Phase Induced Amplitude Apodization Complex Mask Coronagraph (U of Arizona)
4. Hybrid Lyot (Caltech)
5. Visible Nulling Coronagraph (GSFC)
Deformable Mirrors

Need:
- ≥ 96x96 actuators
- pitch sizes ≤ 1 mm
- stroke ≥ 500 um
- radiation and env’t qualified
- flight electronics and connectors

SOA:
- 64x64 electrostrictive actuators by Xinetics (WFIRST baselined 48x48)
  - pitch size = 1 mm
  - stroke = 500 um
- 6x10^{-10} contrast achieved with 32x32

Current Activities:
- 48x48 Xinetics DMs are being flight qualified, connector study, flight electronics design (WFIRST; FY17-18)
- MEMS DMs (BMC and Iris AO) env’t testing (FY18)
- Decadal mission concepts in FY17-18

Deformable mirrors (Xinetics 48x48)
Coronagraph/Telescope Technology Needs

Starlight Suppression

Angular Resolution

Detection Sensitivity

Contrast Stability

- 10 pm rms uncorrected WFE over ~ 10 min
  - few pm sensitivity
  - > 2 OOM greater than WFIRST
- $10^{-11}$ contrast stability
- Systems-level challenge
Wavefront Sensing and Control

**Needs:**
- Few pm rms WFE sensitivity
- Several \((Z \geq 8)\) WFE terms sensed and corrected

**SOA:**
- Zernike wavefront sensor baselined on WFIRST
  - 14 mas simulated jitter input (tip/tilt only) corrected to < 0.5 mas rms residual
  - LoS tilt sensitivity to 0.2 mas and low order modes to the level of 12 pm rms

**Current Activities:**
- WFIRST LOWFS sensing and control of first few modes demonstrated with a telescope and env’t simulator with a coronagraph (FY16); TAC review on Nov 8
Additional Wavefront Stability Technologies

Needs:
- Segment phasing control to < 10 pm rms
- Disturbance: 140 dB at > 40 Hz

Relative to SOA:
- WF stability > 2 OOM better than HST
- 1-2 OOM segment phasing and rigid body control (non-NASA); 3 OOM JWST
- 1 OOM in vibration control (WFIRST)
- Disturbance: 80 dB at > 40 Hz (JWST; passive)

Current Activities
- Decadal mission concepts in FY17-18 to conduct key systems trade studies
  - segmented vs monolith primaries
  - Glass vs SiC segments
  - active control vs passive vs hybrid for thermal, vibration

Note: can be relaxed to SOA for starshade
Detection Sensitivity (Visible)

**Needs (Visible):**
- 0.4 – 1 um ultra-low noise detectors
- Read noise: < 0.1 e’/pix
- Dark current: < 0.0001 e’/pix/s
- Format: > 2kx2k
- Radiation hard

**Relative to SOA:**
- 1kx1k EMCCD baselined for WFIRST
  - Read noise: ok for WFIRST, need better than factor of 2 for HabEx/LUVOIR
  - Dark current: ok for WFIRST, need better than factor of 5 for HabEx/LUVOIR
- Recently environmentally tested (WFIRST)

**Current Activities:**
- Flight R/O electronics design (WFIRST; FY17-18)
- e2V 4kx4k EMCCD being tested at University of Montreal
Detection Sensitivity (NIR)

**Needs (IR):**
- 1-2.5 um
- Read noise: < 1 e'/pix
- Dark current: < 0.001 e'/pix/s
- Format: arrays of ≥ 2kx2k
- Radiation hard
- Zero-vibration cooling

**Relative to SOA:**
- HgCdTe APD Hybrid
- Read noise: << 1 e'/pix
- Dark current: 10-20 e'/pix/s
- Format: arrays of < 1kx1k
- MKIDS and TES are low-TRL cryo solutions

**Current Activities:**
- MKIDS high-altitude balloon demo
- HgCdTe (WFIRST) and HgCdTe APD noise reduction efforts?
- Decadal mission concepts to determine long λ cutoff (FY17)
Coronagraph Technology Needs

Starlight Suppression

Angular Resolution

Wavefront Stability

Detection Sensitivity

- increased sensitivity
- higher throughput
- shorter integration time
- greater planet yield
Large Primary Mirrors

**Needs:**
- ≥ 4 m monoliths and 8-16 m segmented mirrors
- SFE < 10 nm RMS
- Active thermal and figure control for segments

**SOA:**
- Monolith: Herschel’s 3.5 m (SiC); HST’s 2.4 m (ULE, ~ 10 rms SFE)
- Segmented: JWST’s 6.5 m (1.3 m, Be; SFE: < 30 nm rms)

**Current Activities:**
- Non-NASA investments
- Advance Mirror Technology Development (Stahl/MSFC)
  - Validate optical/thermal/mechanical integrated models on a 1.5 m ULE and 1.2 m Zerodur mirrors (FY17)
- Decadal mission concepts will study monolith vs segments, materials, active figure control
Coronagraph/Telescope Technology Needs

Starlight Suppression (Contrast)
- Coronagraph architectures
- Deformable mirrors
- Image post-processing

Contrast Stability
- Wavefront sensing and control
- Segment phasing and rigid body sensing and control

Angular Resolution
- Large monolith
- Segmented

Detection Sensitivity
- Telescope vibration sensing and control
- Ultra-low noise visible and infrared detectors
Recent Starshade Technology News

- NASA-chartered starshade technology activity in March
  - *Starshade Technology Project advances technology to TRL-5*
  - *Starshade Technology Community Meeting on December 1*

- Starshade Readiness Working Group commenced in January to identify the recommended path to flight for a starshade mission.
  - *Multi-institutional working group and participation*
  - *Report out to NASA HQ on November 9, 2016*

- WFIRST is assessing the impact of accommodating a potential future starshade mission
  - *Final decision will be made no later than summer of 2017.*
Starshade Technology Needs

What's not hard...
Starshade Technology Needs

Starlight Suppression

Deployment Accuracy and Shape Stability

Formation Sensing and Control
Starlight Suppression

- Diffraction from starlight
- Reflection from Sun light

**Needs:**
- Contrast $\leq 10^{-10}$ demonstrated near the petal edges at a flight Fresnel number and over different size starshades, wavelengths, and intentional imperfections
- Validated optical models
- Optical edge material identified and integrated to a full-scale petal

**Current Activities:**
- Optical demonstrations underway at Princeton in a 78 m testbed
- Optical performance and modeling studies (Princeton, JPL, NGAS, Colorado) – FY17
- Optical edge manufactured and testing (STP; FY17-18); amorphous metal
- Trade study (STP; FY178)
Deployment Accuracy and Shape Stability

**Needs:**
- Large-scale fully-integrated petal with flight-like materials that meet optical shape tolerances (~70 um rms) and edge scatter performance.
- Large-scale fully-integrated inner disk prototype with flight-like components and opaque membrane that meets deployment tolerances and petal position rqmts (~450 um rms).
- Full-scale petal latching and unfolding mechanism verifying controlled petal deployment with no edge contact during and after launch.

**Current Activities:**
- Deployment trade study (STP in CY17).
- SBIR Roccor developing petal unfolding mechanism.
**Formation Sensing and Control**

**Needs:**
- Sense relative lateral offsets between telescope and starshade to within ±20 cm at 50,000 km distance
  - Measure bearing angle to within ±1.25 mas

**Current Activities:**
- Demonstrating mas bearing sensitivity with feedback control in scaled testbeds (Princeton, JPL; FY17-18)
- Trade study (STP; FY17)
Starshade Technology Needs

Starlight Suppression

- Suppressing scatted light off petal edges from off-axis Sunlight
- Suppressing diffracted light from on-axis starlight

Deployment Accuracy and Shape Stability

- Positioning the petals to high precision, blocking on-axis starlight, maintaining overall shape on a highly stable structure

Formation Sensing and Control

- Maintaining lateral offset requirement between the spacecrafts
- Fabricating the petal to high precision
ExEP Technology Gap Lists

Starshade Technology Gap List

<table>
<thead>
<tr>
<th>Title</th>
<th>Description</th>
<th>Current</th>
<th>Required</th>
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</thead>
<tbody>
<tr>
<td>Light-obstructed coronagraph</td>
<td>Light-obstructed coronagraphs are not yet available.</td>
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<tr>
<td>Coronagraph/Telescope Technology Gap List</td>
<td>Coronagraph/Telescope Technology Gap List</td>
<td>Table A.3 Coronagraph/Telescope Technology Gap List</td>
<td></td>
</tr>
</tbody>
</table>

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

• Engage with the ExoPAG (Program Analysis Group) – the exoplanet community group (http://exep.jpl.nasa.gov/exopag/)

• Propose for a Small Business Innovation Research (SBIR) grant
  – All ExEP technology gaps are mapped to the 2015 NASA Technology Roadmaps
    ➢ http://www.nasa.gov/offices/oct/home/roadmaps/index.html

• Propose for a Strategic Astrophysics Technology (SAT) - Technology Development for Exoplanet Missions (TDEM)
  – TRL 3-5 (http://nspires.nasaprs.com/external/)

• Propose for an Astrophysics Research and Analysis (APRA) grant
  – TRL 1-2 (http://nspires.nasaprs.com/external/)

• Visit the Exoplanet Exploration Program (ExEP) website
  – http://exep.jpl.nasa.gov/

• Contact me directly: nsiegler@jpl.nasa.gov
Acknowledgements

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Government sponsorship acknowledged
Additional Slides
Coronagraphs versus Starshades

Stark et al. 2016
### Table 6.4-3: Key requirements for the error budget. Values are 3-sigma tolerances.

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<tr>
<th></th>
<th>Dedicated 1.1 m</th>
<th>Contrast $\times 10^{-11}$</th>
<th>Rendezvous 2.4 m</th>
<th>Contrast $\times 10^{-11}$</th>
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<tr>
<td><strong>Manufacture</strong></td>
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<tr>
<td>Petal Segment Shape (Bias)</td>
<td>14 $\mu$m</td>
<td>1.4</td>
<td>22 $\mu$m</td>
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<td>71 $\mu$m</td>
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<td>71 $\mu$m</td>
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