

# Astro2020 APC Whitepaper

## Technology Challenges for the Study of Exoplanets and the Search for Habitable Worlds: Status and Path Forward

### ***Principal Author:***

Brendan P. Crill

NASA / Jet Propulsion Laboratory, California Institute of Technology

[Brendan.P.Crill@jpl.nasa.gov](mailto:Brendan.P.Crill@jpl.nasa.gov)

### ***Co-authors***

Nicholas Siegler, Eduardo Bendek, Eric Mamajek, Karl Stapelfeldt

NASA / Jet Propulsion Laboratory, California Institute of Technology

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The decision to implement WFIRST, Origins Space Telescope, HabEx, or LUVOIR will not be finalized until NASA's completion of the National Environmental Policy Act (NEPA) process. This document is being made available for information purposes only.

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# 1. Introduction

This whitepaper outlines the remaining key technology challenges for the study of extrasolar planetary systems, and for the search for life on planets in those systems. The study of habitable, Earth-size planets is a major science goal of several large mission concept studies (HabEx, LUVOIR, Origins Space Telescope) and Probe studies commissioned by NASA, and it has been driving mission-specific technology requirements (Arney et al. 2019). Here we aim to provide an objective assessment of the technological capabilities needed for achieving exoplanet science goals, without advocating for a particular mission approach.

The necessary capabilities include 1) obtaining exoplanet spectroscopy over a broad range of wavelengths; 2) measuring exoplanet mass; and 3) obtaining host-star spectroscopy, particularly in the far ultraviolet. The third capability already exists but requires observations from above the Earth's atmosphere; the first two are already achievable for non-habitable planets much larger than Earth. At the dawn of the 2020s, we are at the verge of pushing these technologies into the realm of habitable, Earth-size worlds, allowing astronomers to collect spectroscopic data that will enable a search for life, and probe the formation histories and diversity of worlds beyond our solar system (Kopparapu et al. 2019).

The capabilities needed to identify Earth-size planets in the habitable zone of Sun-like stars have been reduced to three distinct technology areas requiring advancements to achieve the necessary spectral characterization and mass measurements:

1. Direct imaging of exoplanets (so as to acquire reflection and emission spectra as well as learn their orbital characteristics)
2. Transit spectroscopy (in absorption) / secondary eclipse spectroscopy (in emission)
3. Stellar reflex motion (required for mass measurement and helpful for orbit measurement)

Since the last Decadal Survey, several key advancements toward the search for habitable worlds have transpired: 1. maturation of starlight suppression technologies, namely, coronagraphs and starshades; 2. more accurate measurements of key astronomical quantities, such as the occurrence rates of rocky planets and typical levels of exo-zodiacal dust (Mennesson et al. 2019); and 3. advancements in astrobiology, in particular a better understanding of biosignature gases and scenarios for false positives (Krissansen-Totton et al. 2019). These advances are all summarized in the [National Academies' 2018 Exoplanet Science Strategy report](#).

## 2. Technology Gaps

NASA's Exoplanet Exploration Program (ExEP) identifies technology gaps pertaining to [possible exoplanet missions](#) and works with the community to identify and track technologies to prioritize for investment, and ultimately to close the gaps. The [gaps and technologies](#) are summarized and

captured in detail in their [Technology Plan Appendix](#). A possible roadmap to mature these technologies is described in Crill and Siegler (2017). The gaps in performance, as related to their technology areas, are as follows.

## 2.1. Direct Imaging of Exoplanets

### 2.1.1. Starlight suppression for reflected-light (or emission) spectroscopy

Suppression of starlight in order to capture photons directly reflected from exoplanets requires either starlight occultation or interferometric nulling. Starlight occultation technologies include both internal (coronagraph) and external (starshade) approaches. Both have greatly progressed this decade, largely due to the 2010 Astrophysics Decadal Survey's highest priority recommendation for medium-scale space activities, and, in [response](#), NASA Astrophysics Division's investment in technology development.

#### 2.1.1.1. Coronagraphs

Despite the historical progress of exoplanet discoveries through ground-based telescopes equipped with coronagraphs, even next-generation instruments on future 30-meter-class telescopes will struggle to exceed  $10^{-8}$  contrast sensitivities, due to the residual wavefront errors in atmospheric turbulence correction (Oppenheimer & Hinkley 2009, Currie et al. 2019). The key capability, never achieved in space, is precision wavefront control to advance from  $10^{-6}$  to  $10^{-10}$  contrasts at sub-arcsecond separation.

WFIRST's technology demonstration Coronagraph Instrument (CGI) will be the first high-contrast coronagraph in space equipped with wavefront-sensing and correcting optics to achieve contrast sensitivities between  $10^{-8}$  and  $10^{-9}$ . To observe an Earth-size exoplanet orbiting in the habitable zone of a Sun-like star, however, will [require sensitivities to contrast ratios of  \$10^{-10}\$  or better at visible wavelengths](#). This is 1 to 2 orders of magnitude more demanding than WFIRST's expected performance, and 2 orders of magnitude beyond achievable contrast using future 30-meter-class, ground-based telescopes.

Coronagraph performance demonstrations with apertures resembling telescopes with little or no central obscuration are already close to achieving the  $10^{-10}$  contrast goal while simultaneously achieving relatively high throughput using the NASA-funded High Contrast Imaging Testbed (HCIT) laboratory facility at JPL. An upgraded testbed facility at HCIT called the Decadal Survey Testbed (DST) has been constructed to close the remaining gap between current coronagraph laboratory performance and the contrast goal. With a commissioning Lyot coronagraph, DST demonstrated  $3.8 \times 10^{-10}$  contrast over a 10% band centered at 550 nm, with a working-angle range spanning 3 - 9 resolution elements (wavelength/diameter; Ruane et al. 2019). This facility is now available for users and demonstrations of vortex and hybrid Lyot coronagraph architectures are scheduled for the next year through the competed Strategic Astrophysics

Technology grant program. Ongoing upgrades to DST is expected to improve on this performance in terms of contrast, bandwidth, working angles, and enable demonstrations with obscured or segmented apertures.

Future large space telescopes may comprise segmented mirrors with secondary-mirror obscurations. A number of efforts attempt to address these additional challenges in achieving the same contrast goals while maintaining reasonable throughput and robustness to wavefront errors. In 2016, ExEP chartered the Segmented Coronagraph Design & Analysis study to work with leading coronagraph designers. At the time of this writing, there are three candidates that meet the static performance requirements (Stark et al. 2019) and show acceptable sensitivity to finite stellar diameter and low order wavefront error, while sensitivity to segment-segment phasing errors are currently under investigation (Shaklan et al. 2019). The masks and optics for successful designs will be fabricated, tested in air (starting in 2019) and then tested in the ExEP Decadal Survey Testbed under vacuum. While modeling shows that these designs are feasible, laboratory demonstrations have not fully realized model predictions thus far for unobscured apertures.

#### 2.1.1.2. Starshades

The starshade is currently being advanced under a single ExEP technology development activity, whose objective is to advance five key technologies to Technology Readiness Level ([TRL](#)) 5, and in the process bring the entire starshade to TRL 5. A 26-meter-diameter WFIRST rendezvous starshade is used as a reference mission for the design and engineering work (a starshade, however, is not baselined for the WFIRST mission). While a starshade's optical performance can never be demonstrated at full scale on the ground, a sub-scale demonstration has recently achieved  $1.2 \times 10^{-10}$  average contrast at the inner working angle, at flight-like configurations (defined by the Fresnel number, Harness et al. 2019). To test at these regimes and operate within a practically sized testbed, the demonstration is being conducted with only a 25-mm starshade (the testbed is already 77 meters long; testing large starshade sizes require very long testbeds as separation between the starshade and telescope increases by the square of the starshade radius). Hence, confidence in these sub-scale starshade demonstrations to represent full-scale performance will depend on their ability to validate and exercise the optical performance models. Despite diffraction theory predicting optical performance to be independent of scale, additional suppression demonstrations are planned to be completed by 2020 using a range of key perturbations to demonstrate the robustness of the models.

Another key technology being advanced to achieve the contrast-goal targets is reducing the scattering of sunlight off the starshade's petal edges. Materials that are sufficiently thin, low-reflectivity, and suitable for stowage are being investigated as "optical edges." Amorphous metals are promising candidates and are currently being tested.

Exceeding the capability of existing large structural deployments, the starshade requires precise and stable positioning of a 26-meter or larger structure to better than 1 mm. A stowage and deployment design based on petals wrapped around a central truss that deploys using a standard RF antenna design, has been developed and demonstrated on sub-scale prototypes. A half-scale or larger prototype is planned for demonstration of deployment tolerances and necessary stability. The technology is likely to be directly applicable to starshades up to roughly 50 meters in diameter. If a future mission requires a much larger starshade, new deployment technology may be required.

#### 2.1.1.3. Coronagraph Contrast Stability

Due to the extremely low rate of photons detected from distant exoplanets (in the range of about a photon per minute in the case of the WFIRST coronagraph), performing spectroscopy at a sufficient signal-to-noise ratio will require the contrast to be maintained for long integration periods. In the case of coronagraphy, this translates to maintaining wavefront errors to within 10 - 100 pm rms on timescales of roughly 10 minutes, with the exact stability requirements depending on spatial and temporal frequencies, and on the coronagraph architecture. While instrument-level lab demonstrations to date are within a factor of a few of this requirement, this is 1 to 2 orders of magnitude more demanding than the performance of current and upcoming space telescopes. The Hubble Space telescope achieved 25 nm stability per orbit (although in a much more challenging thermal environment of low-Earth orbit as compared to L2).

This level of extreme wavefront stability must be maintained as the space observatory and its coronagraph experience typical environmental disturbances during operation, such as dynamic jitter from reaction wheel mechanisms and thermal drifts from varying heat loads. Large mirrors, both monolithic and segmented, will be challenged by the need to achieve a stable back-structure and segmented ones will need to maintain a large number of individual segments working in concert to create a paraboloid. Due to these tight stability requirements, coronagraphs can no longer be designed as separate payload instruments but rather, along with the observatory, as an integral system. Analyses by the HabEx and LUVOIR study design teams have determined approaches to meeting these challenges for space-based telescopes over a range of telescope sizes, and NASA has funded systems-level segmented space telescope studies that have begun detailed thermal and mechanical analyses of notional architectures, with stringent wavefront error stability requirements as a key driver (Coyle et al. 2019, Dewell et al. 2019). These studies have not identified any show stoppers for a segmented space telescope compatible with a coronagraph instrument, but they enumerate many challenges that require further system-level modeling and new technology development. Advances are required in the areas of mirrors and mount structures, disturbance reduction, and active sense and control to enable a wavefront that is stable at the picometer level. These represent the biggest challenges for coronagraphy.

Note that in the case of a starshade-only mission, telescope stability requirements are significantly looser and do not exceed the state-of-the-art (SOA). A solution for sensing and controlling alignment between the two spacecraft have been developed and demonstrated at subscale in the lab. Thus, the technology development for missions that utilize starshades falls primarily on the starshade itself, and not on the optical telescope assembly. This may be an important risk mitigator if the telescope stability requirements prove to be too challenging for a coronagraph instrument tasked to image Earth-size planets.

#### 2.1.1.4. Detection Sensitivity

The extremely low reflected-light flux from rocky exoplanets requires a detector with read noise and spurious photon count rate as close to zero as possible. This detector must also maintain adequate performance in a space environment, as it is occasionally bombarded by solar and galactic particles. The SOA is dependent on the wavelength band, but detectors must perform at or near the photon counting limit from the UV through NIR for current mission concepts. Across this wavelength range, the SOA detectors are semiconductor-based devices. WFIRST's EMCCD (electron multiplying charge coupled device) detectors have achieved adequate noise performance in the visible band, though longer lifetime in the space radiation environment is desirable, as is better performance at long wavelengths. Similar EMCCD devices, but with delta doping, may already have adequate performance in the near-UV. HgCdTe detectors are the SOA in the NIR with or without an avalanche gain stage. It is likely that the detection sensitivity gap can be closed in the next decade, as a range of choices are close to meeting the requirements.

#### 2.1.1.5. Angular Resolution and Collecting Area

Large space telescopes offer many benefits in determining exoplanet habitability, such as tighter point spread functions (greater sensitivity to faint objects), improved spatial resolution (to probe the habitable zones of more distant stars), improved spectral resolution (for better feature signal-to-noise), shorter integration times (offering the possibility of studying different faces of a rotating planet in a nearby star system), and better rejection of the extended diffuse brightness of exozodiacal light (which could obscure exoplanets). All else being equal, these advantages allow larger-aperture telescopes to obtain a larger exoplanet yield (Stark 2019), a benefit that may prove to be very important if the frequency of habitable planets is small, as well as higher signal-to-noise ratio data for a given target.

The largest monoliths flown in space to date are the 2.4-meter Hubble Space Telescope, optimized for visible and UV astronomy, and the Herschel Space Observatory's 3.5-meter telescope, optimized for the far-IR. The James Webb Space Telescope (JWST) will establish the SOA in mid-IR space telescopes with a 6.5-meter primary mirror made up of 18 co-phased hexagonal beryllium segments. Current large mission concept studies feature telescope apertures ranging from 4-meter monoliths to 15-meter segmented telescopes. Large monoliths

would advance exoplanet science but are not on a technology path to larger (segmented) telescope apertures that may be desired later.

Large glass monoliths are commonly fabricated for ground-based telescopes. If future heavy-lift launch vehicles, such as NASA's Space Launch System, become a reality then the opportunity for 4- to 8-meter-class monoliths become a possibility. Large monoliths will advance exoplanet science but will not directly lead to subsequent larger telescope architectures. Mirrors constructed from one-meter class silicon carbide or glass segments have fabrication heritage and appear to be promising options, although requiring multiple levels of closed-loop control of surface figure in order to meet coronagraph contrast goals. The benefit of segmented primary mirrors is the ability to build on the JWST heritage and fold larger apertures for stowage into smaller fairings. For example, a 15-meter aperture can be designed to fit into a 10-meter fairing (e.g. LUVOIR). For even larger aperture sizes (exceeding 15 meters), implementation may require assembly in space (Mukherjee et al. 2019).

## 2.2. Transit/secondary Eclipse Spectroscopy

### 2.2.1. Spectroscopic Sensitivity

To enable precise transit or secondary-eclipse spectroscopy of exoplanets, the detector response must exhibit photometric stability over the timescales of a transit, typically hours. Spitzer's IRAC instrument has achieved photometric stability of order 60 parts per million on transit time scales. JWST's MIRI is expected to achieve a similar stability between 10 - 100 ppm. The Origins Space Telescope large mission study finds that stability of 5 - 10 ppm in the mid-IR is needed in order to measure the atmospheres of Earth-size planets transiting nearby M-dwarfs.

The path to close the technology gap in transit spectroscopy of Earth-size planets is challenging. Astrophysical limits should be examined further to find the likely fundamental limits to stellar stability to determine whether these will dominate over instrumental requirements. The sources of instability in detector/telescope systems must be studied to determine where future technology investments will be most effective. Photometric instabilities of a mid-IR detector system may be driven by fundamental detector materials properties, cryogenic detector readout circuitry, or other instabilities in the system. This should be investigated along with modeling the on-orbit calibration and other spectrograph configurations, which could mitigate the detector requirements to some level. Performing these measurements with JWST in the early 2020s will provide valuable lessons (Beichman et al. 2019).

## 2.3. Stellar Reflex Motion

### 2.3.1. Radial Stellar Motion Sensitivity

Radial velocity (RV) measurements of the reflex motion of a star is a way to infer the minimum mass and orbital parameters of planets orbiting the star (Ciardi et al. 2019, Dressing et al. 2019). The reflex motion of a solar-mass star due to an orbiting Earth-mass planet at 1 AU is  $\sim 10$  cm/s over 1 year, and both measurement and systematic errors must be kept in the  $\sim 1$  cm/s region. The HARPS instrument at the La Silla Observatory has recently achieved sensitivity to 70 cm/s signals. The next generation of ground-based RV instruments coming online in the next two years (including NEID on the WIYN telescope) are expected to achieve 20-30 cm/s instrumental sensitivity per measurement.

While there are several important uncertainty sources in closing this gap, the biggest is understanding the astrophysical limits due to the natural jitter of the star. At the time of this writing, the path forward to achieving 1 cm/s sensitivity to close this technology gap is unclear. The challenge could be mitigated with a broad wavelength range of observations and observing from space (should tellurics prove to be the limiting factor; Plavchan et al. 2018), and through experience at mitigating systematic errors in ground-based RV instruments measurements (creating an ultra-stable environment, developing extremely precise calibrators such as laser frequency combs). To help address these questions and develop a strategy, ExEP has commissioned an initiative in Extreme Precision Radial Velocity.

### 2.3.2. Tangential Stellar Motion Sensitivity

By performing sensitive astrometry of a star over time, the mass and orbital parameters of orbiting exoplanets can be measured (with arbitrary orbital plane inclination). The European Space Agency's Gaia's initial data release achieved typically 300 micro-arcsecond ( $\mu$ as) position error, but subsequent data releases are expected to achieve 10  $\mu$ as sensitivity in the positions of many stars, enough to reveal thousands of Jupiter-mass exoplanets. However, detecting Earth-mass planets at a distance of 10 pc demands orders of magnitude improvement in precision (to about 0.3  $\mu$ as per measurement). Although models predict astrometry's ultimate sensitivity, limited by starspot jitter, to be substantially higher than that of RV observations (Makarov et al. 2009), the inherent instability of stars will need further understanding, along with characterizing sources of instrument instability, to ascertain theoretical performance predictions. Such investigations will require exquisite calibration and modeling using techniques such as interference fringes or diffractive pupils (Bendek et al. 2019, Shao et al. 2019).

### 3. Future Technology Needs

Any of the above-mentioned large exoplanet missions under study, with the technology needs outlined above, will be sensitive to detecting biologically-produced gases in the atmospheres of Earth-size planets in the habitable zone of their stars. Extraordinary claims will require extraordinary evidence, and the evidence to rule out abiotic mechanisms will require more data. This data will need to be collected at additional wavelength ranges beyond the capability of one observatory. This may require a subsequent mission to confirm or rule-out possible life hypotheses to conclusively answer the question, “Are we alone?”

If the first “bio-hints” are detected via spectral features in the UV-NIR, a subsequent mission could provide supportive (or inconsistent) evidence in the mid-IR. This would allow a more thorough search for methane (CH<sub>4</sub>) and carbon dioxide (CO<sub>2</sub>), adding more information to help piece the story of what may actually be occurring on the surface of these distant worlds (note, a reversed mission sequence could also work). However, because it becomes impractical with a single-aperture telescope to resolve the habitable zones of nearby stars in the infrared even at 15 μm wavelength (where the important CO<sub>2</sub> feature is present), interferometry may ultimately be the approach of choice where the resolution is set by the baseline between multiple apertures rather than the size of the individual telescopes. Interferometry was studied in the early 2000’s as part of NASA’s Terrestrial Planet Finder Interferometer concept, whose study identified technology gaps in path-length stability, detector sensitivity, passive and active cryogenic cooling, and formation flying. Interferometry is also a key technology for the “Visionary Era” of NASA’s Astrophysics Roadmap (Kouveliotou et al. 2013), including an Exo-Earth Mapper that would achieve spatial resolution across the surface of an Earth-size exoplanet. Investments in technologies to close these gaps should begin no less than 15 years before mission start.

Alternatively, a search for secondary biosignatures could occur with a more sensitive telescope that allows for the detection of smaller spectral features. This could be achieved by larger single-aperture optical telescopes. Eventually, such telescopes, even when folded, may exceed the largest possible rocket fairing creating a compelling need for in-space assembly.

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