Technology development for continued progress in characterizing exoplanetary systems via radial velocity and direct imaging observations

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Introduction

Among the most important science themes defining future NASA missions such as WFIRST, LUVOIR and HabEx is the quest to characterize the properties of Earth-like planets and their host planetary systems. To achieve these goals requires continuous work on the technologies and methodologies that are possible with existing and upcoming facilities and instruments. We briefly summarize several areas of progress and future technology development required to detect and characterize potentially Earth-like planets via direct imaging and radial velocity observations.

Areas of Recent Progress

Advanced Coronagraph and Adaptive Optics Technology. Ground-based adaptive optics coronagraphs continue to deliver significant results while laying the groundwork for future facilities, that when combined with 20–40-m Extremely Large Telescopes (ELTs) will play an important role in the characterization of Earthlike planets around nearby low-mass stars [31]. For example, the Gemini Planet Imager, VLT SPHERE, and Subaru ScExAO systems have produced high-fidelity spectra of giant planets, precision astrometry, and are exploring the outer parts of young solar systems[28, 4, 23]. Current systems on 8-m class telescopes, however, are limited to observing young giant planets around relatively distant stars; but they are also serving as testbeds to develop techniques and technology that will enable future characterization of Earthlike planets from ground-based and space telescopes. They have provided key opportunities to develop and validate wave front sensing and control technologies and a platform to explore and advance sophisticated methods necessary for high-contrast data analysis. Meanwhile, NASA continues to fund development of the technology needed for high-performance coronagraphs in space.

The Large Binocular Telescope. The Large Binocular Telescope Interferometer (LBTI) is comprised of two 8.4-m mirrors separated by 14.4-m center-to-center on a common mount. Both telescopes employed adaptive optics systems operating at visible wavelengths, allowing very high quality wavefront error correction with very high throughput to the instruments because of the adaptive secondary mirror. At mid-infrared wavelengths, the LBTI is the most sensitive instrument in the world due to only three warm reflections before the beams enter cold optics.

Beams from both telescopes have been combined coherently with NOMIC instrument [21], and the LMIRCAM instrument [27], which offer both Fizeau (image plane) and Michelson (pupil plane) combination schemes. NASA has funded the development of the NOMIC instrument, which is being used for the Hunt for Observable Signatures of Terrestrial Planets (HOSTS) study [8].

This study has recently set new limits for exozodi detection for solar-type stars [15]. With roughly half of the sample (∼30 stars) observed, the detection rate is comparable for both early type and solar type stars, ranging from ∼60% for stars with cold dust previously detected and ∼8% for stars without such an excess. Assuming a lognormal excess luminosity function, the upper limits on median Habitable Zone (HZ) dust is 29 zodis (95% confidence limit) for Sun-like stars not having currently detected cold dust. The upper limits for stars without an excess detected by the LBTI are approximately a factor of two lower. These recent results demonstrate the power of LBTI for vetting potential targets for future direct imaging missions such as LUVOIR or HabEx, and the importance of completing and enlarging the study in the next few years.

The WFIRST Coronagraph Instrument (CGI) may provide additional information about the properties of the dust detected by the LBTI, as the CGI instrument will observe scattered light from dust rather than thermal emission detected by the LBTI. The two measurements taken together allow for analyses of the physical properties of the dust grains including morphology and chemistry.

New Data Processing Techniques. Significant post-processing is required to detect exoplanets, even after the suppression of starlight from coronagraphs. The challenge is to remove the residual stellar glare without also removing the light from much fainter exoplanets. The application of principal component analysis (PCA) to high-contrast imaging data has provided the best technique so far to remove the noise of the star while also maintaining the signal of the planet [38]. On top of PCA, sophisticated forward modeling techniques applied to integral field spectroscopy (IFS) data have been developed to obtain sub-milli-arcsecond accuracy on the position of exoplanets (for orbit determination) as well as integrated into reliable planet detection algorithms whose performance can be numerically quantified [34, 40, 37]. Establishing confidence in algorithms that can precisely detect and characterize imaged exoplanets in IFS data will be crucial for future missions to image reflected light exoplanets, which are several orders of magnitude fainter. These algorithms have also been released in open-

[1] https://bitbucket.org/pyKLIP/pyklip
[2] https://github.com/vortex-exoplanet/VIP

source software packages like `pyKLIP` [1] and `VIP` [2] to ensure accessibility.

The large exoplanet surveys undertaken by GPI and SPHERE have also provided an invaluable testing ground for developing and validating data processing software. The GPI Exoplanet Survey developed a data processing infrastructure that fully automates the storing, indexing, and processing of survey data while also providing convenient human-interfaces for accessing the data [41]. The tooling and techniques will be useful for future surveys to image Earth-like planets, whose single-year orbital periods necessitates quick turnaround on data processing for following up candidates. Radial velocity campaigns spanning multiple observatories could benefit from similar data processing infrastructure.

Extreme Precision Radial Velocity. As radial velocity (RV) programs have moved to larger telescopes and upgraded instruments, multiple groups have achieved sufficiently precise RV measurements, that stellar variability has become the dominant noise source for a large fraction of their target stars [3, 16, 20, 18]. Initially, the RV community assumed that the measured RVs could be represented as the sum of true Doppler shift and an independent Gaussian noise whose magnitude was accurately estimated from the RV pipeline. At the time, when modeling relatively RV-quiet target stars, modelers could generalize their analysis model to allow for an addition noise source ("RV jitter"), again assuming that the perturbation due to each measurement was independent of measurements at other times [17]. This allowed for more accurate estimates of planet masses and orbital parameters, particularly for long-period planets where less than two orbital periods had been observed.

To realize the full potential of next-generation Doppler planet searches and to discover Earth-mass planets in the habitable zone of Sun-like stars, it will be essential to develop observational strategies that obtained phase coverage required and statistical methods to make full use of the information collected [16]. Observers have already begun to pilot observing strategies to mitigate different types of stellar activity (e.g., intensely observing a smaller number of stars, rather than more sparsely observing a larger target list). For example, surveys can increase exposure times to average over p-modes, make multiple observations over one night to characterize granulation, and observe for as many nights as possible within a season to characterize spots, faculae and other rotation-linked variability.

In principle, stellar variability can be distinguished from planets due to three effects: 1) true radial velocity changes induce the same Doppler shift across the entire stellar spectrum, while the amplitude of stellar variability typically varies with wavelength; 2) stellar variability is more complex than a simple Doppler shift, as it can distort the depth, width and shape of spectral lines, rather than being a simple shift; and, 3) a single planet induces a strictly periodic perturbation with a stable amplitude, period and phase, but stellar activity is typically in quasi-periodic on timescales associated with stellar rotation, magnetic activity cycles, and/or convection. Therefore, the independent Gaussian noise model is no longer adequate for state-of-the-art RV searches since intrinsic stellar variability can masquerade as an apparent radial velocity shift. The community has begun to make progress modeling stellar variability as a correlated noise source and modeling stellar activity indicators and planetary perturbations simultaneously [35, 22].

Likely Progress Over the Next 20 Years

Direct Imaging Techniques for ELT's. Three fundamental processes define the future roles for ground and space-based observatories. First, rapidly-changing optical aberrations due to atmospheric turbulence mean that even the best ground-based system will never be have the same absolute sensitivity floor as an optimized space telescope. Second, the inner working angle is inversely proportional to telescope diameter. Finally, since the separation of the habitable zone scales with stellar type, the relative brightness of a habitable zone planet orbiting close to a low-mass star is much higher than that of a habitable zone planet orbiting a solar-type star. This produces a natural complementarity, where space-based facilities can access the habitable zones of solar-type stars while ground-based facilities are our best potential window into the habitable zones of the very nearest M stars. Ground-based telescopes can also incorporate instruments with very high spectral resolution, opening up detailed characterization of planetary atmospheres.

Significant investment in several key technologies is required to take advantage of this complementarity. Deformable mirrors, low-noise IR detectors, coronagraphs optimized for very small inner working angles, high-contrast spectrographs, etc. are not mature at the level needed for an ELT planet imager. While all three ELT programs—the Thirty Meter Telescope (TMT), European ELT (EELT) and Giant Magellan Telescope (GMT) are interested in habitable-planet imaging science—none has identified funding for a exoplanet imager instrument in their first suite of capabilities, as their communities prioritize extragalactic science. In this landscape, there is a clear opportunity for coordinated participation by multiple federal agencies.

Wave Front Control. Only young, self-luminous extrasolar gas giants have been directly imaged. Direct detection of low-mass, comparatively low luminosity exoplanets will require significant improvements in starlight suppression. Limitations in adaptive optics systems are a key limitation. For example, in the few milliseconds between sensing the wave front and correcting it, the wave front undergos significant evolution. Such servo lag errors due to rapid atmospheric seeing or spacecraft vibration spill starlight into the coronagraph's inner working angle where planets are most likely to reside. Theoretical work and some on-sky deployment, indicate that predicting the shape of the wave front at the instant of correction can improve contrast performance by an order of magnitude [33, 19, 7]. Fundamental work needs to be done on algorithm development, evaluation, implementation, and testing. Preliminary efforts have investigated linear quadratic Gaussian controllers and empirical orthogonal functions. More general approaches, including Kalman filtering and machine learning should be explored. The field should pursue development of predictive wave front control that couples to detector development (for wave front sensors) and high performance real time computational platforms (e.g., FPGAs and GPUs [5, 39]).

Direct Imaging in the Mid-Infrared – The Road to Space Interferometry Missions. The infrared spectral region (3–28 μm) is well-known for its richness of molecular features from bands of molecules such as ozone, carbon dioxide, water vapor, nitrous oxide, methane, ammonia, and the hydroxyl radical [24]. Direct imaging of exoplanets and characterization missions and relevant technologies at these wavelengths were studied in the last decade such as the large Darwin/TPF-I [6] and the Probe class mission FKSI [9]. Ground-based prototypes demonstrating relevant technologies and obtaining important science were the Keck Interferometer Nuller (results in [30], and the LBTI HOSTS project [21, 8].

Considerable technology development for mid-infrared nulling interferometers began with the Keck Interferometer Nuller (KIN), and recently the LBTI that have provided the most sensitive observations to date of the luminosity function of warm debris disks in the habitable zones of nearby solar type stars. Testbeds for space interferometers (TPF-I/Darwin/FKSI) have also been developed in the US and Europe that are room temperature. Future testbeds are needed at cryogenic temperatures to fully develop technologies for these to mimic conditions in space with realistic signal and noise levels, as well as likely spacecraft disturbance sources.

Recent studies of star-planet interactions, including the interaction of coronal mass ejections with the atmospheres have shown that the atmosphere of the Earth (viewed as an exoplanet) responds strongly in the mid-infrared and cools through mid-IR lines of OH, NO, and other molecules [1]. There has also been renewed interest in the potential of mid-infrared spectroscopy of exoplanet atmospheres[13],[14].

A Potential Roadmap to the ExoEarth Mapper. The upcoming decade can be used to prepare and develop mission concepts that lead to the ExoEarth Mapper, an interferometric space facility envisioned beyond the 2030s [25]. The community must pursue technology development in this area in order for this vision to be realized.

At present, with modest technology investments it is possible to develop a Probe Class mission concept that could lead to a future flagship mission, such as the ExoEarth Mapper [25]. For example, the ground-based nulling interferometer concept "High Contrast Interferometry up to 5 Microns," or "Hi-5" short[14]. Hi-5 takes advantage of progress in integrated optics, nulling, closure phase, and statistical data reduction, and will use the four Unit Telescopes (UTs) and/or four Auxiliary Telescopes (ATs), at L band and M band, providing inner working angles of order of 2 mas at 3.8 microns. Such a system will achieve L band contrasts of the order of 10^{-4}, sufficient to observe 10 M_{Jup} planets with ages from 1 to 100 Myr. Such an instrument could also provide a follow-on to exozodiacal disk science where interesting correlations between very cold dust observed in far-IR excesses by Spitzer & Herschel, and mid-IR excesses observed by Spitzer & LBTI can be compared to non-correlations between these observations and the discovery of hot excess observed with CHARA and VLTI[30, 15]. Such observations are necessary to unravel the competing physical processes in mature disk systems that contribute to the various observed excesses. Such studies are particularly important to exoplanet direct detection missions as exozodiacal dust, particularly if clumpy, is the main astrophysical noise source affecting their ability to detect and characterize exoplanets in the Habitable Zones of nearby solar-type stars.

The next step is developing space interferometry. To that end a balloon-borne interferometer has been under development at NASA/GSFC[36]. This instrument, "Balloon Experimental Twin Telescope for Infrared Interferometry," (BETTII) is a far-IR interferometer operating between 30–100 μm at altitudes of over 30 km and above much of the Earth's atmosphere. This instrument is currently being rebuilt and is expected to fly again in about 2-3 years.

Beyond balloon-borne interferometers, probe level concepts such as FKSI [9] and PEGASE [32] were described in the 2009 Exoplanet Community Report[10]. Most of the enabling technologies (e.g., sun-shades, cryocoolers, low-noise mid-IR detectors, and stable deployable booms) for these missions have been used on JWST and NuSTAR. An enhanced version of FKSI, called "Exolife Beacons Space Telescope" or ELBST is also under development[2].

With sufficient technology investment, such programs provide a pathway to a future flagship "vision" mission to image and characterize nearby exoplanets. While the ExoEarth Mapper was conceived as a formation flying ensemble of a large number of telescopes, moon-based solutions are also just starting to be discussed, primarily in Europe, e.g., ICMOONS. The temperature at the bottom of permanently shadowed craters in the lunar poles, can be as low as 30K, sufficient for star and planet formation and exoplanet studies.

Improved Detectors. Detector improvements of most importance to direct imaging observatories include obtaining the highest quantum efficiency possible over a broad bandwidth, ability to count single-photons, negligible dark currents and read noise and energy resolution. These detectors must also be radiation tolerant at the level of 50-100 kilorads for a 5–10 year lifetime.

Furthermore, the detection system (including the telescope and other components) must be extremely stable over time periods of a few hours, in order to maintain the very high precision needed for key science.

Among the most promising and revolutionary technologies are those that use microwave kinetic inductance detectors (MKIDs) for high-contrast imaging. MKIDs are a superconducting detector technology wherein a photon breaks an energy-dependent number of Cooper pairs[26]. The resultant change in Cooper pair density briefly changes the surface impedance, which can be measured using microwave multiplexing techniques[12].

MKIDs can detect individual photons at UV, optical, and near-IR wavelengths with time resolution of a few microseconds and measuring individual photon energies to within a few percent[29]. Photon counting and simultaneous spectroscopy provided by MKIDs enable real-time speckle control and post-processing speckle suppression. MKIDs also have enormous potential as detectors for wave front sensors, including as focal-plane wave front sensors.

MKIDs technology is maturing rapidly. Active research programs are needed to improve pixel count and yield, energy resolution, and anti-reflection coatings to improve detector quantum efficiency. In parallel, development of high bandwidth data systems is needed to capture high data rates from megapixel arrays.

Extreme Precision Radial Velocity. The precision RV community has devoted considerable attention to the stabilization of instruments and precision calibration[16]. While important, these efforts do not address the primary source of "noise" for most nearby stars, is their intrinsic spectroscopic variability due to processes such as spots, faculae, granulation, convection and pulsations. Upcoming radial velocity spectrographs[42] with increased resolving power, spectral range, and signal-to-noise will be capable of measuring more information than is contained in traditional stellar activity indicators [11, 22]. Similarly, instrument builders have begun designing instruments with broader wavelength coverage and/or higher resolution, so as to provide additional and/or improved spectroscopic diagnostics that can be used to inform modeling of stellar variability. The above innovations mean the current and next-generation RV surveys can provide much greater information about the stellar variability, allowing for modelers to shift from treating stellar variability as noise to treating it as a signal to be modeled.

In contrast to the above investments instrumentation and telescope time, there has been relatively little investment in developing rigorous, yet tractable statistical models that can extract information provided by the spectroscopic time-series. This is related to, but distinct from, developing software pipelines to extract "cleaned" spectra or even Doppler measurements from raw data. Pipelines are clearly an essential element, but can only deliver what was asked of them. Currently, the field has yet to demonstrate that any realistic data product from a funded instrument is capable of detecting an Earth-like planet in the habitable zone of nearby Sun-like stars.

Fortunately, there are several avenues that have not been adequately explored and have considerable potential for improving the RV sensitivity of upcoming Doppler surveys. Opportunities for investment include: 1) developing improved spectroscopic diagnostics of stellar variability by adapting (several) existing machine learning algorithms for application to spectroscopic time-series; 2) developing sound statistical frameworks for interpreting spectroscopic time-series that exploit the rich spectroscopic information, rather than reducing each spectrum to a RV, sigma and a couple of activity indicators; 3) comparing the performance of such models by analyzing simulated data sets with different model assumptions for the properties of stellar variability to understand what data needs to be collected in order to resolve degeneracies and characterize stellar variability tightly enough to detect low-mass planets; 4) expanding models so they can be applied to realistic datasets (e.g., telluric absorption, telluric variability, increasingly realistic stellar variability, imperfections in wavelength scale, etc.); 5) supporting observational campaigns which emphasize the collection of unusually-high quality RV datasets with the primary purpose of testing models in a data-rich setting (e.g., intense observations of Sun and a very small number of other stars); and 6) supporting teams including both astronomers and statisticians to refine concepts into robust tools that are both astronomically-motivated and statistically sound (e.g., comparing the performance of different activity diagnostics and statistical models in the presence of increasingly realistic data sets).

Summary

We recognize that technology developments coupled with novel approaches to data reduction and analysis will continue to yield important progress in the discovery and characterization of exoplanets and the search for life.

For Doppler surveys to characterize Earth-mass planets in the habitable zone of nearby stars, we will need to make significant investments in advancing the state-of-the-art in diagnostics for stellar variability and statistical modeling to incorporate that information into a joint model for planets and stellar variability. Future radial velocity surveys will require devoting significantly more telescope time per star in order to obtain sufficiently high resolution, signal-to-noise and density of sampling to model stellar variability and characterize Earth-mass planets.

Adaptive optics wave front measurement and control are the keys to very high contrast imaging both on ground- and space-based telescopes. The combination of improved control systems (predictive control), wave front sensors employing high-performance detectors, and advanced point-spread-function subtraction algorithms will find giant planets formed via core accretion and yield the first objects and jointly detected by imaging and the Doppler method. There are important technological synergies between filled aperture imaging and interferometry, which should be developed and exploited. At the key mid-infrared wavelengths associated with important molecular species, ground-based, sub-orbital, and space-based interferometers require special emphasis.

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