A Technology Validation Program for near-IR Habitable Exoplanet Imaging with GMT and TMT

Corresponding Author:
Olivier Guyon, (Univ. of Arizona, Subaru/NAOJ, and Japanese Astrobiology Center)

Co-Authors:
Michael Bottom (University of Hawaii)
Mark Chun (University of Hawaii)
Laird Close (University of Arizona)
Kristina Davis (University of California Santa Barbara)
Michael P. Fitzgerald (University of California Los Angeles)
Richard Frazin (University of Michigan)
Phil Hinz (University of California Santa Cruz)
Rebecca Jensen-Clem (University of California Berkeley)
Nemanja Jovanovic (Caltech)
Hajime Kawahara (University of Tokyo)
Quinn Konopacky (University of California San Diego)
Julien Lozi (Subaru/NAOJ)
Jared Males (University of Arizona)
Christian Marois (NRC-Herzberg and University of Victoria)
Dimitri Mawet (Caltech)
Benjamin Mazin (University of California Santa Barbara)
Norio Narita (Astrobiology Center)
Garreth Ruane (Jet Propulsion Laboratory)
Steph Sallum (University of California Santa Cruz)
Eugene Serabyn (Jet Propulsion Laboratory)
Andy Skemer (Jet Propulsion Laboratory)
Motohide Tamura (University of Tokyo, NAOJ, and Japanese Astrobiology Center)
Gautam Vasisht (Jet Propulsion Laboratory)
Shelley Wright (University of California San Diego)
Ji Wang (The Ohio State University)
Takayuki Kotani (NAOJ and Japanese Astrobiology Center)
R. Deno Stelter (University of California Santa Cruz)
1. EXECUTIVE SUMMARY

The upcoming ground-based US Extremely Large Telescopes (GMT and TMT) will be powerful exoplanet characterization facilities addressing a wide range of exoplanet science cases.

Among these, imaging and spectroscopic characterization of rocky planets in the habitable zones of nearby stars stands out as particularly ambitious, requiring advances in the achievable contrast and inner working angle on large segmented apertures beyond what has been demonstrated to date. In this paper we highlight ongoing developments in promising approaches and technologies, and present a technology development roadmap to reaching those contrast goals, including demonstration and facilitization on current- and next-generation facilities in the laboratory and on large telescopes.

This roadmap enables improvements both in the “raw” contrast delivered by the wavefront control and starlight suppression systems, as well as in the final contrast realized through the combination of specialized backend instrumentation and post-processing techniques. Milestones along this road map include the design and validation of coronagraphs optimized for segmented apertures, the development of high-speed high-actuator-count deformable mirrors, the refinement of high-speed low-noise detectors as applied to both pupil- and focal-plane wavefront sensing, predictive wavefront control, sensor fusion, coherent differential imaging, and specialized low-order mode sensing and control techniques. On-sky validation, combining coronagraphy, adaptive optics and signal extraction will be performed on existing large ground-based telescopes.

2. Key Science Goals and Objectives

US ELTs will offer the angular resolution and sensitivity to characterize a wide range of exoplanets and disks in thermal emission and reflected light. While most US ELTs exoplanet science investigations will simply leverage the telescopes’ large collecting area and high angular resolution without relying on significant technology advances, characterizing potentially nearby habitable worlds will require integrating advanced technologies in a high contrast imaging (HCI) instrument.

US ELTs will provide the first opportunity for direct imaging and spectroscopy of potential habitable planets orbiting the nearest stars. Two approaches appear particularly promising: (1) reflected light (near-IR) imaging and spectroscopy of rocky planets in the habitable zones of the ~50 nearest low-mass stars (M and possibly K type), and (2) thermal (~10 um) imaging and spectroscopy of Earth-like planets around the ~5 nearest Sun-like stars. The near-IR reflected light observations, which are the focus of this paper, will measure (spectroscopically) oxygen, water, methane and other molecular species indicative of a habitable environment and biological activity.
The vital role that ground-based astronomy will play in detecting life outside our solar system was recognized in the 2018 National Academy Exoplanet Science Strategy report (https://doi.org/10.17226/25187):

**Finding:** The GMT and TMT will enable profound advances in imaging and spectroscopy of entire planetary systems, over a wide range of masses, semimajor axes, and wavelengths, potentially including temperate Earth-size planets orbiting M-type stars.

**Finding:** The technology roadmap to enable the full science potential of GMT and TMT in exoplanet studies is in need of investments, leveraging the existing network of U.S. centers and laboratories and current 8-10 meter class facilities.

**Recommendation:** The National Science Foundation (NSF) should invest in both the GMT and TMT and their exoplanet instrumentation to provide all-sky access to the U.S. community.”

The 2018 NASA Strategic Plan (https://science.nasa.gov/about-us/science-strategy) also states “Are we alone?” as a central research question.

The NAS report and the NASA Strategic Plan codify the community consensus on the importance of exoplanet imaging and spectroscopy to our future understanding of exoplanets and life in the Universe. Despite this consensus, there is no organized program to drive forward our ability to detect and characterize exoplanets with US ELTs.

We describe key technical challenges, ongoing development activities and outline here a path through which high contrast imaging (HCI) technologies can be developed, matured and validated within the 2020-2030 decade to enable GMT and TMT instrumentation capable of identifying habitable environments on the surfaces of the nearest exoplanets early in the next decade.

### 3. Technical Overview & Challenges

**Due to the high star-to-planet contrast ratios and small angular separations, near-IR reflected light habitable planet observations will require new technologies and approaches.**

The most promising targets for US ELTs will be rocky planets orbiting in the habitable zones of nearby M-type stars. Thanks to the star’s low luminosity, the reflected light contrast of a hypothetical Earth-like planets, at ~1e-8, is approximately 3 orders of magnitude more favorable than for a Sun-like star. This contrast level is potentially within the reach of large ground-based telescopes equipped with high performance extreme adaptive optics (ExAO) systems and starlight suppression devices, and GMT and TMT large collecting areas enables spectroscopic characterization.

To overcome the large star-planet contrast ratio, exoplanet imaging observations require a HCI system combining three key functions: (1) high performance adaptive optics wavefront correction (achieved by an Extreme-AO system), (2) starlight suppression (provided by a
coronagraph), and (3) high-accuracy signal extraction (differential imaging and post-processing techniques). Two HCI instruments combining the three functions have already been in routine science operation on large ground-based telescopes since 2014: the Gemini Planet Imager and VLT’s SPHERE. While simply re-deploying similar instruments on US ELTs would allow characterization of numerous young giant planets with unprecedented sensitivity, they would fail to deliver the contrast required to image and characterize potentially habitable planets (something they were never designed to do).

For a HCI system to image and characterize potentially habitable planets, it must deliver, at the minimum a 1e-5 raw contrast at 30 mas (≈2 λ/D) angular separation, and, additionally, extract a 1e-8 contrast signal within the residual starlight (Guyon et al. 2018).

To meet the required improvements in contrast and inner working angle, technology advancements must address a number of new key challenges, including:

- **ExAO high order adaptive optics correction** must be performed over a large telescope aperture. At a minimum, 10,000 modes must be corrected at a few kHz to achieve high quality correction in the near-IR, a ~10x increase in degrees of freedom over current ExAO systems.
- The ExAO system must address wavefront chromaticity between visible WFS and near-IR science camera, and wavefront amplitude (scintillation) errors (Guyon 2005), while current ExAO systems only tackle achromatic optical pathlength difference.
- **ExAO wavefront sensing sensitivity** must be improved to deliver reliable and accurate real-time measurements of residual wavefront errors on nearby M-type stars, which are, in visible light, ~10x to 100x fainter than the conventional targets of current ExAO systems.
- ExAO wavefront control must include exquisite real-time sensing and correction of non-common path aberrations (NCPAs) that currently limit most ExAO systems. NCPAs currently set a lower detection limit at ~1e-6 contrast at small angular separation, so a ~100x improvement is required.
- **Coronagraph performance** must be pushed to deliver raw contrast exceeding 1e5 at 2 I/D from the optical axis while maintaining high throughput, and be sufficiently resilient to low-order aberrations. This performance level has not yet been demonstrated on a ground-based system on-sky: coronagraphs currently in operation on ExAO systems operate most efficiently at 4 I/D and beyond.
- The coronagraph must operate on a segmented aperture, while current ExAO systems only address central obstructions and spiders
- By combining differential imaging and post-processing techniques, the HCI system must be capable of extracting scientifically valuable signal (spectral features, polarization signal) approximately 2 to 3 orders of magnitude below the residual starlight halo, and operate near the photon noise limit.
4. Technology Status and Promising Opportunities

**High contrast imaging technologies have advanced considerably over the last decade, providing compelling solutions to the HCI challenges previously described.**

4.1. Key hardware components to realize a GSMT-scale ExAO system (almost) exist

Thanks to advances in computing power, detectors and deformable mirrors technologies, an ELT-scale ExAO system can be realized within the 2020s:

- Fast photon-counting detectors now exist in both visible and near-IR (Atkinson et al. 2018, Meeker et al. 2015), and are suitable for high sensitivity, high-speed wavefront sensing. Modest improvements to meet the required pixel count are required and are being pursued, and do not pose major risk.
- Current (2019) computing capabilities can already drive an ELT-scale ExAO system with a conventional linear controller, and continued exponential improvements (Moore’s law), now largely supported by hardware acceleration (GPUs, FPGAs), will enable more advanced control schemes.
- At a component level, the most challenging technology remains the deformable mirror (DM): currently commercially available DMs offer up to 64x64 actuators, while at least 128x128 actuators are required. The scaling to this actuator count, already initiated in Europe by ESO, will require a multi-year engineering effort at a cost of a few million US$, but does not pose major risks. Alternatively, the telescope pupil may be split in a few large sub-pupils, each corrected by a single smaller DM (this option is a natural fit to the GMT pupil segmentation).

4.2. Managing mirror segmentation

Segmented apertures present unique challenges for coronagraphy and wavefront control:

- Coronagraphs can be designed to handle edge diffraction from gaps. Much progress has been accomplished in coronagraph designs for “unfriendly” pupils, in part thanks to the challenge posed by WFIRST’s centrally obscured aperture.
- New wavefront sensors are capable of measuring phase discontinuities across gaps. Diffraction-limited wavefront sensors (Pyramid, focal plane) provide this capability with high sensitivity.

4.3. Smarter, more sensitive wavefront sensing

Advances in wavefront sensing and related technologies will bring orders-of-magnitude gains in sensitivity:

- While current major ExAO systems (GPI, SPHERE) rely on seeing-limited Shack-Hartmann wavefront sensors, **diffraction-limited sensors**, such as the Pyramid, Zernike or focal plane WFS are now in operation on multiple ground-based AO system (Pyramid WFS at Keck, LBT, Subaru, Magellan). The sensitivity difference is considerable for large telescopes, and is expected to be especially significant if the AO
system can deliver diffraction limited performance at the WFS wavelength. This new type of sensor is therefore especially well suited for ExAO systems.

- **New detector technologies** now offer photon-counting performance from visible to near-IR, some with wavelength resolution (MKIDs). They enable efficient broadband wavefront sensing.

- Improved wavefront sensing architecture, employing multiple WFSs, can address scintillation (amplitude errors) and differential wavefront chromaticity (between a visible WFS and a near-IR camera) that, if left uncorrected, would limit raw contrast to \(-10^{-4}\).

- **Model-based wavefront sensing**, in which the control signal is a numerical estimate of phase of the wavefront obtained by analysis of the WFS telemetry (as opposed to a calibration of the responses to DM pokes) is a new frontier. Among other benefits, it provides the ability to solve the phasing problem of ELTs (Schwartz et al. 2018), as well as treating nonlinearities in the wavefront sensor (Frazin 2018, Hutterer et al. 2018).

- **Predictive control**, by extrapolating the current state of wavefront aberrations from the set of most recent measurements, allows for photon noise to be averaged over a longer time span, resulting in improved sensitivity and contrast (Males & Guyon 2018).

- **Sensor fusion** approaches can optimally combine measurements from multiple WFSs potentially spanning a wide wavelength range, therefore further improving sensitivity. Additionally, sensor fusion techniques allow for non-optical sensors (accelerometers, thermometers, etc.) to contribute to wavefront estimation.

Many of the above gains are not simply multiplicative, but strongly benefit each other. For example, with smaller residual wavefront errors, wavefront sensors become more sensitive, more linear, and better calibrated, which improves predictive control efficiency.

### 4.4. Focal plane wavefront sensing, coherent differential imaging

While conventional AO systems rely on pupil plane wavefront sensing, focal plane wavefront control (FPWFC) approaches make use of fast-frame focal plane images to estimate residual starlight, measured as coherent speckles. The approach addresses several of the key HCI challenges:

- By design, FPWFC is insensitive to non-common path errors
- FPWFC is very sensitive, making optimal use of starlight photons
- FPWFC can be deployed at or near the science wavelength, so it does not suffer from atmospheric chromaticity limitations

Several variants of FPWFC have been proposed for active wavefront control, including classical speckle nulling (Martinache et al. 2014, 2016), electric field conjugation (Groff & Kasdin 2013, Matthews et al. 2017, Sun et al. 2018) and linear dark field control (Miller et al. 2017). Jovanovic et al. 2018 provide a detailed review of this field. FPWFC has been most successful in laboratory settings where residual wavefront errors are small and slow, but on-sky results have so far been slow to bear fruit due to algorithmic (non-linearity) and hardware (camera sensitivity and speed) challenges. These limitations are being addressed thanks to deployment of high performance detectors on ExAO systems and new algorithms / software implementation.
FPWFC can also be extended to coherent differential imaging, where the coherent (starlight) and incoherent (planet) components are estimated in real-time. This can be implemented as an algorithmic extension to focal plane wavefront sensing approaches using wavefront modulation for probing (Gerard et al. 2018). Alternatively, both pupil plane and focal plane WFS telemetry can be used to co-estimate both components without requiring DM probes, using the measured dynamic AO residual wavefronts themselves as the probes (Frazin 2019).

4.5. Real-time PSF estimation
An ELT HCI instrument will likely include multiple WFSs (for example, a pupil plane WFS and a fast focal plane imaging camera). Collectively, these sensors hold sufficient information to reliably estimate the residual starlight component in real-time, and therefore subtract it from the science data to reveal faint planets. The residual starlight speckles that currently limit exoplanet imaging sensitivity should no longer be an unknown noise: each speckle signature is also contained in the WFS telemetry. New approaches to exploit this information and perform real-time PSF estimation are emerging and becoming possible thanks to advances in computing capacity. An empirical approach could rely on machine learning techniques (Neural Networks) to relate WFS telemetry to focal plane images using training sets. A more deterministic approach would use an accurate computational model of the system (Frazin 2019). Hybrid empirical/deterministic approaches should also be explored.

4.6. Differential detection approaches
Current ExAO systems mostly rely on field rotation (angular differential imaging - ADI) and wavelength-scaling of the speckle halo (spectral differential imaging - SDI) to separate exoplanet light from the residual starlight halo. These approaches perform poorly at very small angular separations, and significantly more powerful approaches, many of which rely on kHz frame-rates in the science camera, have matured over the last decade:
- In **high dispersion coronagraphy** (Wang et al. 2017, Mawet et al. 2017), sets of narrow molecular absorption lines are detected to identify specific species. The narrow spectral features provide a clean differential detection signal, absent in the starlight.
- **Coherent differential imaging** approaches use coherent mixing between speckle halo and starlight to separate the coherent (starlight) and incoherent (planet light) components.
- **Polarization differential imaging** is benefiting from recent advances in detector technologies, allowing high-speed polarization modulation synchronized with detector readout (Norris et al. 2015).
- **Stochastic Speckle Discrimination** with photon counting detectors appears to be a promising way to beat the classical photon noise even at small inner working angles (Walter et al. 2019, arXiv:1906.03354)

Note that all of these can be unified with focal place wavefront sensing in a common regression framework that jointly estimates both the planetary image and the non-common path aberrations (Frazin 2019).
5. Organization, Partnership, and Current Status

We are growing and integrating existing facilities and projects in a coherent effort focused toward addressing key technology challenges for exoplanet imaging instruments on GMT and TMT.

The technology validation program is jointly developed in support of the GMagAO-X (Astro2020 APC paper, Males et al.) and TMT-PSI (Astro2020 APC paper, Fitzgerald et al.) instrument concepts. The two instruments share common technical challenges and technology needs.

5.1. Key elements

We envision a program that integrates the following key elements:

   A. Fundamental R&D (for example, understanding atmospheric turbulence, new control algorithms)
   B. Laboratory prototyping (components: coronagraphs WFS, DM, detectors; systems: HCI testbeds)
   C. End-to-end performance simulation, integrated modeling and instrument architecture design
   D. On-sky prototyping and validation

The centerpiece of the program will be a new effort to support on-sky testing (D), backed by laboratory (B) and simulation capabilities (A, C), for demonstrating new hardware, algorithms, and observing strategies. On-sky validation is vital since no laboratory-based simulator has been able to capture the diversity of challenges an exoplanet imaging instrument encounters on-sky. The consensus in the community is that on-sky validation on current large telescopes (5-10 m diameter) is an effective risk-mitigation approach, and is the most reliable path toward adoption of new technologies by GMT and TMT, where telescope time will be too precious for risky time-consuming experimentation. The modeling and simulation effort will link test results with instrument architecture choices and science yield, and therefore ensure that on-sky validation activities are mapped to GSMT instrument scientific priorities.

5.2. Why a new program?

Elements of the proposed program already exist, but have not yet been efficiently integrated toward deployment of exoplanet instrumentation for GMT and TMT. Small-scale research...
activities provide some of the fundamental R&D activities needed to develop new technologies, but the path to maturation is not straightforward and too long for inclusion in GSMT instruments in the early 2030s. Similarly, high contrast imaging laboratory activities (mostly funded by NASA in the US) focus on specific technologies (for example, coronagraph masks) and do not capture the system-level complexity, challenges and environment of a ground-based instrument. Despite the rapid development of HCI approaches and technologies, it is very difficult to assess which approaches are most relevant, mature, and to what degree they will actually perform in a full on-sky system. While several new approaches are poised to bring order-of-magnitude gains, lack of on-sky experience leads to poor understanding of actual system-level performance and associated risks and uncertainties.

A new effort is required to address this bottleneck between the early technology development phase, and the maturation level that meets the demands of a GMT or TMT instrument. Lacking such a program, the next generation of exoplanet imaging GMT and TMT instruments will miss their most scientifically rewarding opportunities due to well-justified risk-averse decisions.

5.3. Leveraging existing and upcoming facilities

The on-sky validation program will include dedicated telescope time, allocated competitively based on value to GSMTs exoplanet imaging instrumentation. Existing and emerging instruments will be leveraged, among which:
- The Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) instrument
- The Keck Planet Imager and Characterizer (KPIC)
- The Magellan extreme-AO system (MagAO-X)

These three facilities are already engaged in technology maturation for GMT and TMT, and offer complementary capabilities. Subaru’s SCExAO is a hybrid science instrument / development platform providing a relevant system-level test environment and an instrument architecture representative of a future instrument. Keck’s KPIC provides a segmented aperture telescope test platform, and focuses on combining high spectral resolution with coronagraphy. The MagAO-X system will probe higher actuator density providing access to shorter wavelengths.

The three instruments are already working toward adopting common software interfaces and code to facilitate collaborative activities.

A support team (engineers, postdocs) dedicated to the program will prepare instrumentation for the tests, perform off-sky and on-sky measurements and ensure that the required data is collected and adequately processed. This support team will overlap with instrument(s) team(s) from the respective facilities, but will be dedicated to the program rather than the short-term science operation needs.

Laboratory testing, necessary to validate technologies prior to on-sky deployment, will leverage the same instrument/facilities, used in daytime testbeds. This ensures the shortest path from lab to on-sky validation and optimally prepares teams for on-sky testing. Some component/subsystem testing will also be performed at other existing and/or future testbeds in Universities and National Labs.
5.4. Cost and Schedule
The total activity cost is estimated at $3M/yr over a decade ($30M total cost) excluding development cost for individual components (detectors, DMs):

- The technology validation program’s dedicated support team (program manager, engineers, postdocs, some hardware support) will cost $1M/yr.
- The associated telescope time required for the program, about 5 nights per year among major observatories will cost $500k/yr.
- Integrated modeling, essential to tie together on-sky validation, scientific yield estimates and instrument design choices, will cost an additional $1M/yr.
- Fundamental R&D, focused on a few high-priority topics, will cost $500k/yr.

The activity goal is to enable GMT and TMT instrumentation capable of mapping habitable environments around nearby stars in the 2030 decade. It is the most ambitious/challenging science goal of GSMT exoplanet imaging instrument(s) that will perform a wider range of less risky scientific observations, including detailed characterization of giant exoplanets. We envision that the proposed technology validation activity would span the 2020 decade, and overlap with instrument(s) construction in the second part of the decade.

For example a modular, phased approach is envisioned for the TMT-PSI instrument (Fitzgerald et al, 2019), where the longer wavelength, less challenging part of the instrument (PSI-RED) will be deployed first, while the shorter wavelength arm that would image habitable planets in reflected light (PSI-BLUE) continues to be developed to more challenging requirements.

Similarly, the GMagAO-X instrument concept (Males et al, 2019) seeks to deploy HCI instrument hardware early on and subsequently continue development to push instrument performance. We also note that much of the proposed developments will focus on improving AO control software and post-processing, and can be developed independently of hardware.

6. References


