Overview of Technology Development for the Phase-Induced Amplitude Apodization (PIAA) Coronagraph

Ruslan Belikov
Ruslan.Belikov@nasa.gov
650-604-0833
NASA Ames Research Center, Moffett Field, CA

Co-Authors

Roger Angel	*University of Arizona*
Asfaw Bekele	*Tinsley Laboratories*
Kerri Cahoy	*NASA Ames Research Center*
Michael Connelley	*NASA Ames Research Center*
Lee Dettmann	*Tinsley Laboratories*
Donald Gavel	*UCSC*
Amir Give'on	*NASA Jet Propulsion Lab*
Olivier Guyon	*University of Arizona / Subaru Telescope*
Daniel Jay	*Tinsley Laboratories*
N. Jeremy Kasdin	*Princeton University*
Rick Kendrick	*Lockheed Martin*
Brian Kern	*NASA Jet Propulsion Lab*
Marie Levine	*NASA Jet Propulsion Lab*
Dana Lynch	*NASA Ames Research Center*
Mark McKelvey	*NASA Ames Research Center*
Bridget Peters	*Tinsley Laboratories*
Eugene Pluzhnik	*NASA Ames Research Center*
Laurent Pueyo	*NASA Jet Propulsion Lab*
Titus Roff	*Tinsley Laboratories*
Eugene Serabyn	*NASA Jet Propulsion Lab*
Stuart Shaklan	*NASA Jet Propulsion Lab*
Michael Shao	*NASA Jet Propulsion Lab*
Clay Sylvester	*Tinsley Laboratories*
Wesley Traub	*NASA Jet Propulsion Lab*
John Trauger	*NASA Jet Propulsion Lab*
Robert Vanderbei	*Princeton University*
Fred Witteborn	*NASA Ames Research Center*
Robert Woodruff	*Lockheed Martin*

1 Executive Summary

Direct imaging and spectral characterization of an Earth-like extrasolar planet (exo-Earth) is one of the most exciting goals in astrophysics, one that appeals as much to the layman as to the scientist, one with philosophical ramifications and historical significance, and one that is possible to achieve in the coming decade with a space telescope as small as 1.4m.

One of the few technologies that can enable this is the Phase-Induced Amplitude Apodization (PIAA) coronagraph [1], which can provide contrast levels of 10^{10} at an inner working angle of 2 λ/D with almost no loss of throughput. This powerful performance is close to the theoretical limit of any possible coronagraph [2] and enables exo-Earth imaging of nearby stars with relatively small telescopes. Furthermore, PIAA has already received significant laboratory testing and holds the world record in laboratory-demonstrated contrast at 2 λ/D.

The purpose of this white paper is to describe the current state of PIAA technology, the path forward to TRL6, and the level of effort and time required to realize it. Several instances of the PIAA coronagraph have been built and are currently undergoing laboratory testing in the visible. Contrasts of several times 10^7 have already been demonstrated in monochromatic light in air in two labs (at Subaru telescope and NASA Ames Research Center) at 2 λ/D and a vacuum test is about to take place at NASA JPL's High Contrast Imaging Testbed (HCIT) facility, where contrasts of $\sim 10^9$ and better have been achieved in a 10% wavelength band with other coronagraphs (at less aggressive inner working angles and throughput levels). Significant progress has therefore already been made, but further development and support is necessary to bring PIAA to full maturity. Fortunately, the technology is reasonably well understood at this point and a clear path forward can be defined. In particular, the main technology drivers requiring advances are manufacturing of the PIAA mirrors, wavefront control architecture and algorithm design, instrument pointing and dynamics, and system modeling. We recommend a technology development program to mature these technologies culminating in a vacuum demonstration of a full PIAA coronagraph system operating with 10^{10} contrast levels at 2 λ/D across several spectral channels simultaneously across the full visible band.

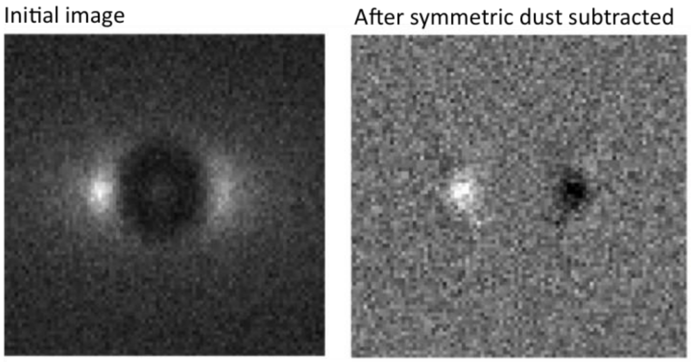
Note that this white paper complements a general one [3] that overviews all the technologies for direct optical imaging of exoplanets. That paper advocates a robustly funded technology program that first funds the most promising concepts, including PIAA and several other internal coronagraphs, as well as an external occulter, and eventually downselects one of them once it becomes clear which one is most optimal. We second this recommendation, and essentially provide details here that describe the PIAA branch of this program.

This white paper also complements a "request for information" submission [4] that describes a specific mission based on PIAA called Pupil-mapping Exoplanet Coronagraphic Observer (PECO) [5]. This mission has been the subject of a recent NASA Astrophysics Strategic Mission Concept Studies (ASMCS) effort. One of the outcomes of this study was the design of a 1.4m PIAA telescope capable of directly imaging nearby exoEarths in 16 spectral channels, with a lifetime cost of $800M. While the PECO mission is currently the primary beneficiary of the PIAA technology, the intent of this paper is to focus on PIAA technology separated from any specific mission, and instead describe the full range of possibilities that PIAA makes possible in the next decade.

2 Science Enabled by PIAA

PIAA technology enables direct imaging and spectral characterization of exo-Earths (Earth-mass planets in the habitable zone of their stars) around nearby stars even with a relatively small aperture space telescope (Figure 1). In addition, such a telescope will also be great at imaging and characterizing larger planets and circumstellar dust disks. The best-studied case is the PECO mission [4,5], which in a 3-year mission lifetime achieves the following goals:

- Search for Earths and Super-Earths in the habitable zones of 20 nearby stars
    - Planet detection and orbital constraint: 16 hr integration x 10 visits per system
    - Planet characterization: assume 5 detections, 2 x 400 hr integration each with S/N ~ 30 and spectral R = 15. This includes searching for biomarkers such as water and oxygen.
    - Disk characterization to 1 zodi sensitivity with color and polarization is included for each observation
- Characterization of 15 known RV planets
    - Planet orbital constraint: 16 hr integration x 3 visits per system
    - 200 hr integration x 2 visits each with S/N > 30
- Snapshot survey of 120 circumstellar disks and giant planets
    - System characterization: 16 hr integration time each



Telescope D (m)	# Earths 450 nm	# Earths 672 nm
1.0	5	2
1.2	10	5
1.4	19	8
1.6	32	14
1.8	42	20
2.0	52	30

Figure 1. Left: Simulated PECO images of an Earth-like planet around Tau Ceti in a 400-500nm band with an exozodi comparable to the solar system. Photon noise and 16 electrons total detector noise for an electron multiplying CCD have been added. 47 Uma b. Right: Simulated performance of PECO at different wavelengths and telescope diameters.

Even though the best-studied case is the probe-class PECO mission, PIAA technology is equally applicable to smaller or larger missions. A PIAA telescope as small as 0.5m can still do substantial science on giant planets and dust disks. Such a telescope can even be flown on a balloon [6]. A flagship-class (~4m telescope size) PIAA mission is capable of searching hundreds of stars for earths and spectrally characterizing some of them with an R approaching 100, similar to TPF-C flight baseline 1 [7], but with a telescope half the size. This type of a mission will unambiguously detect Earth-like levels of oxygen and water and find other potential indicators of life if it exists on exoplanets.

Finally, PIAA can be used with ground-based telescopes and is in fact currently being prepared for installation on the Subaru telescope, scheduled for early 2010. Unlike space, PIAA does not enable exo-Earth imaging from the ground, but it does enable high contrast imaging at smaller angular separation than more conventional coronagraphs. Young self-luminous giant planets in relatively small orbits (~5 AU at the distance of the Taurus group of young stars) can therefore be imaged, and the inner regions of known protoplanetary disks can be probed.

The main theme is that PIAA's high-performance capabilities can contgribute to both exoplanet science and exozodiacal dust disks across a wide variety of platforms, and potentially directly image exo-Earths in the coming decade. Furthermore, PIAA's near 100% coronagraphic throughput at inner working angles that approach the diffraction limit (2 λ/D) in general enables more science than many other coronagraphs for a given telescope.

3 Technology Readiness

In this section, we describe the state of the PIAA technology and its subsystems, and identify the ways in which these need to be advanced. For reference, we will use the baseline PECO architecture (see Figure 2) as an example of a coronagraphic imaging telescope based on PIAA. The scope and focus of this paper is mainly the instrument part of the full system (starting with the dichroics in Figure 2) and omit the discussion of the telescope and EMCCDs, which are already covered well by [3,4]. We first describe the state of various subsystems and the development needed, and then present a concise summary in the form of a table at the end of the section.

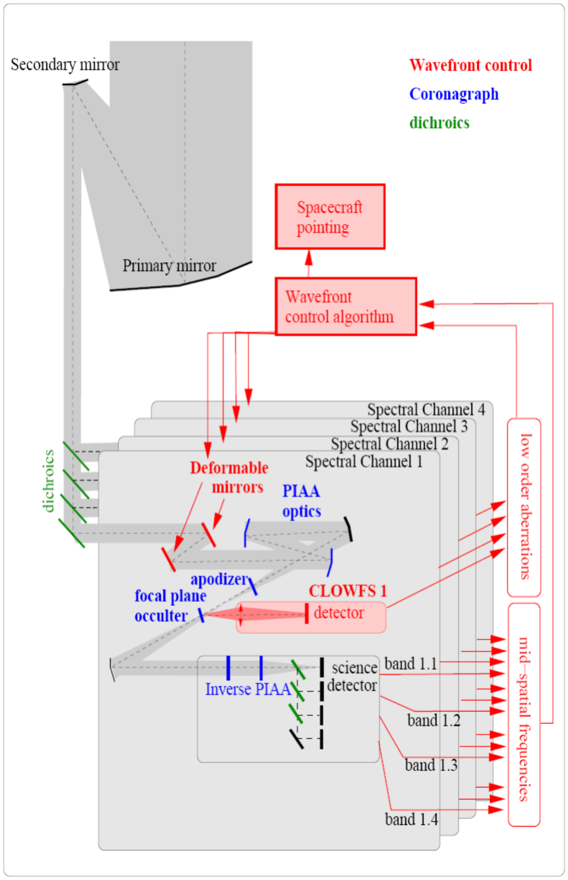


Figure 2. PECO Architecture

3.1 Hardware

3.1.1 Multiple Channels / Dichroics

In the design in Figure 2, the full 0.4 to 0.9 micron spectral coverage is divided in 4 channels with 4 bands each (16 spectral bands total). Light is first split into four spectral channels by dichroic filters. This split is necessary to reduce chromatic effects in the wavefront control and coronagraph subsystems.

The number of spectral channels (somewhat arbitrary chosen to be 4 in this baseline) is tuned to balance system complexity and ability to achieve high contrast in broadband. Analysis and laboratory verification of the wavefront control and coronagraph performance in broadband is essential to choose the correct number of spectral channels.

Light is further split in narrower spectral bands at the detector level in each spectral channel. This second split is motivated by the scientific need for spectral resolution. In the baseline design shown, each spectral channel is split in 4 bands by a set of dichroics. The total number of spectral bands is 16 (4 spectral channels x 4).

Dichroics are critical for enabling this spectral imaging capability of PIAA. In particular, the dielectric layers need to be very uniform, because otherwise there will be unwanted polarization and chromatic effects. In addition, dichroics will introduce some ghost images that must be eliminated and some spectral dispersion for the transmitted channel.

Laboratory demonstrations conducted to date have focused on demonstrations of a single coronagraphic channel, and while these demonstrations yielded impressive and promising results (see section 3.3), the multi-channel operation of the system with dichroics remains largely unexplored and is one of the main targets for future development.

3.1.2 Wavefront control (WFC) system

The wavefront control system is shown in red in Figure 2. Wavefront control is necessary even on a space telescope because (a) the wavefront quality required for exo-Earth imaging is a couple of orders of magnitude greater than can be achieved with static optics, and (b) there are slight dynamical misalignments and pointing errors in space, even though they are slower than atmospheric seeing. In each spectral channel, the wavefront is first corrected by a set of two DMs (but this is not the only possible architecture). Two DMs are necessary to correct both for phase and amplitude errors in the wavefront, as well as to provide some level of chromatic control.

The wavefront errors can be sensed by the science detectors using DM diversity and an algorithm such as the Electric Field Conjugation (EFC) [8] can be used for wavefront control. Variants of this scheme have been used successfully in the Subaru and Ames labs (see section 3.3) in a single channel in monochromatic light to get to a few times 10^7 levels, and one is being developed for use at HCIT. Simulations show that 10^{10} contrast levels are attainable with a low enough error on the PIAA mirrors.

The current PECO baseline uses eight Xinetics DMs, which are 48mm in size. With this many relatively large DMs on a relatively small telescope, there is a strong incentive to test smaller DMs, such as the Boston Micromachines MEMS DMs, and this technology is currently being explored at the NASA Ames testbed.

In addition, trade studies are necessary to answer the following two critical questions related to wavefront control architectures.

(1) What is the best system architecture? Should the DMs and/or PIAA system be before or after the channel-splitting dichroics? Should the DMs be before or after the PIAA system? These options essentially represent a tradeoff between optical design simplicity and performance. For example, the PECO study has shown that placing DMs before the PIAA system offers better outer working angle (field of view), but requires a "reverse PIAA system", which raises system complexity. Further theoretical investigations and laboratory architecture studies are necessary to optimize performance.

(2) How to optimally combine wavefront sensor signals from all channels? The wavefront sensing in each channel contains the information about the common errors (ones that occur before the dichroics and are therefore common to all channels) and the differential errors (ones that occur after the dichroics and are different in different channels). Extracting that information in the presence of noise in each channel, and separating the common errors from the differential errors may be a challenge but needs to be addressed by simulations and lab tests.

3.1.3 PIAA Coronagraph Optics

The PIAA coronagraph optics are shown in blue in Figure 2 (PIAA mirrors + apodizer + focal plane mask). The PIAA mirrors are the heart of the PIAA coronagraph and the entire imaging system. They are specially shaped aspheric mirrors that reshape the pupil plane beam from a uniformly illuminated beam to a special apodized illumination profile that has a shape similar to a Gaussian. The result of the pupil apodization performed by the PIAA optics is that essentially all of the star PSF is concentrated inside an almost diffraction limited spot 2 λ/D in radius, as opposed to the standard Airy pattern which has Airy rings that extend very far and completely overwhelm any planet light. This high contrast PSF from the star can then be blocked by a simple hard-edge focal plane occulter, without blocking planets. (The function of the "apodizer" is to slightly help with the apodization that is mostly performed by the PIAA mirrors.) For more in-depth description of the PIAA coronagraph design, see [9,10].

3.1.3.1 PIAA mirrors

The PIAA mirrors are the most challenging component of the system to manufacture because they are highly aspheric (by many hundreds of waves) and they have to be made very precisely. Two generations of PIAA mirrors sets have been manufactured to date (we'll refer to them as PIAAgen1 and PIAAgen2), as well as a number of independent sets of PIAA lenses. Lenses are appropriate for ground-based telescopes where contrast requirements are "only" $\sim 10^6$ and an on-axis refractive PIAA design can remove the telescope central obstruction, but they are too chromatic at the 10^{10} contrast level and suffer from uncorrectable ghosts. Mirrors seem to be the only choice for 10^{10} contrast in broadband light. PIAAgen1 is a first-generation set of mirrors and was manufactured by Axsys. PIAAgen2 is a second, and latest, generation set and was manufactured by Tinsley. PIAAgen2 benefits from a higher performance design (in particular, better broadband performance). Lenses and PIAAgen1 have been tested in the lab and PIAAgen2 is about to be tested at HCIT and at Ames (see below). Figure 3 (left) shows one of the PIAAgen2 mirrors and its obvious asphericity. The surface error (low-pass filtered at 20 cycles per aperture) for both of the mirrors was better than 3nm rms. When perfectly aligned, the (filtered) single-pass measured system wavefront is around 10nm rms, except for the very edges of the mirrors (see Figure 3, center). These edges can be removed by an appropriate apodizer design, however.

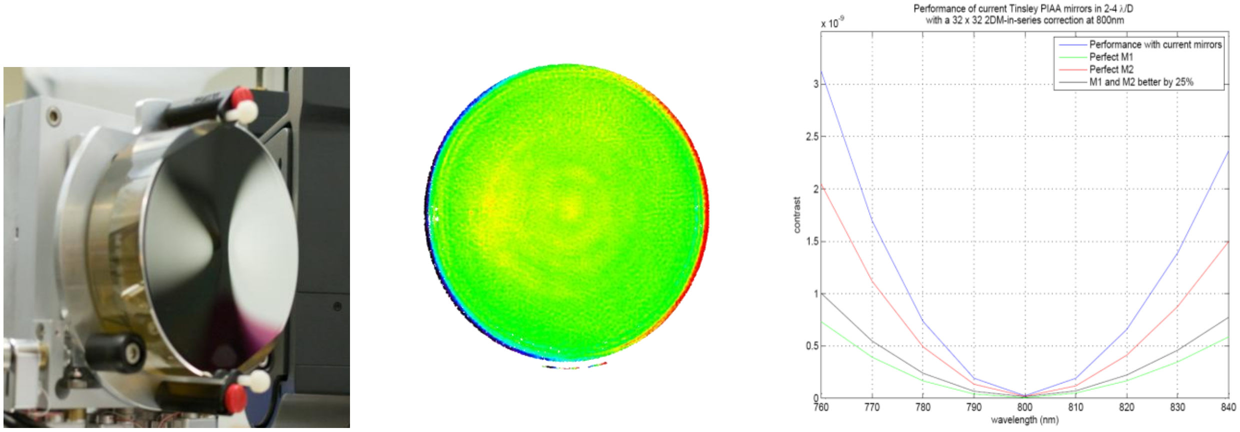


Figure 3. ***Left*: a PIAA mirror, showing obvious asphericity. *Center*: Double-pass wavefront measurement of the aligned PIAA2 system at JPL's HCIT (color stretch is 1.8 waves). *Right*: Order-of-magnitude estimate of wavefront control performance for such a system. For this simulation, perfect correction was set at the central wavelength (800nm) and the degradation at other wavelengths was computed.**

A contrast performance estimate of wavefront control with the known errors on the PIAAgen2 mirrors is shown in Figure 3 (right). It is correct to about a factor of 3. The graphs show that there is an uncorrectable chromatic error in a 10% wavelength band (from 760nm to 840nm), around a 10^9 contrast level. So, unfortunately these mirrors don't seem to be adequate for 10^{10} contrast in broadband light, but fortunately the cause of this error is known and can be eliminated. Namely, this uncorrectable error is caused by what is known as "frequency folding", or beating, of the errors on the mirrors with spatial frequencies outside the control range of the DM (higher than 24 cycles per aperture for a DM with 48 x 48 actuators). It turns out that a factor of 2 or 3 reduction in the level of these "mid-spatial frequencies" will reduce this effect to below 10^{10} contrast, and this seems within the realm of capability for Tinsley. Once we reach close to theoretically predicted 10^9 contrast with the current PIAAgen2 mirrors, they can either be smoothed further, or a third generation (PIAAgen3) set can be built with further design improvements and with acceptable levels of mid-spatial frequencies.

3.1.3.2 Apodizer

An apodizer mask is necessary to prevent the surfaces of the PIAA mirrors having unreasonably high curvature and to prevent unwanted diffraction effects [9,10]. This apodizer incurs only a slight throughput loss (10%). The apodizers currently designed look like a set of concentric rings, and manufactured by depositing aluminum on a glass with a wedge (to prevent ghosts). It is not fully certain that such a transmissive element will not cause problems at 10^{10} contrast levels, and it is worthwhile to investigate alternative apodizer designs that, unlike a concentric ring mask, can be made free-standing. There is considerable experience in making free standing masks [11], and so this effort will be mainly in designing the shape of the apodizer appropriate for a free-standing mask.

3.1.4 Low-Order Wavefront Sensor (LOWFS)

The starlight blocked by the focal plane stop isn't discarded, but rather redirected to be used for efficient sensing of low order aberrations. The Coronagraphic Low Order Wavefront Sensor (LOWFS) system uses the large amount of light from the star, and can measure pointing, focus and a few other low order modes at high speed (~kHz) and with sufficient accuracy to maintain high contrast. The LOWFS has been demonstrated at the Subaru testbed to within a factor of 2-4 of what's needed for 10^{10} contrast.

3.2 Modeling

The most difficult part of the system to model is the propagation between the two PIAA mirrors. There are a half-dozen or so different ways to model this, but they can be grouped into two general classes: geometric optics-based methods that are generally fast, but not very accurate and diffraction-based methods that are slow but accurate. It is thought that for a properly designed PIAA system where diffraction has been suppressed, the fast geometric methods are sufficient, and so far most of the modeling involving wavefront control has been based on geometrical optics methods. Diffraction methods are used only when designing the PIAA system to verify that diffraction has been suppressed. This strategy has been validated in the lab to at least 10^7 contrast levels in monochromatic light, but it is not clear whether it will continue being sufficient down to 10^{10} and in broadband light.

3.3 Current performance

PIAA technologies have been undergoing lab testing at Subaru for a number of years, and recently that effort is being transferred to a new testbed at Ames (see section 4). Furthermore JPL's HCIT is about to begin vacuum testing of PIAAgen2. The results to date of these labs are shown in Figure 4. All testing so far involves only a single channel of the system in Figure 2, and with a single MEMS DM (made by Boston Micromachines) downstream from the PIAA optic, in monochromatic light, but both HCIT and Ames will be working in broadband light and with multiple DMs in the near future.

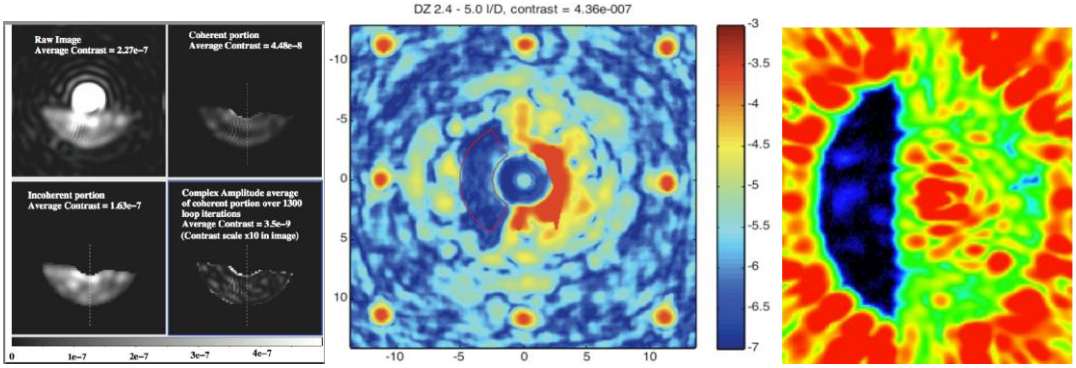


Figure 4. ***Left***: **Subaru testbed, 2e-7 contrast from 1.6-4 λ/D, monochromatic light;** ***Center***: **Ames testbed, 4e-7 contrast from 2.4-5 λ/D, monochromatic light;** ***Right***: **HCIT (BLC Coronagraph), 8e-10 contrast from 4-10 λ/D in 10% band.**

Aside from all the needed technology development described in previous sections, experience shows that attaining high contrast in the lab requires exquisite mecahnical and thermal stability of the testbed environment and all the components and signals, careful baffling, and control of contaminants. A significant portion of the work needed for technology development effort needs to be spent on improving the testbed environment rather than the instrument to be tested. (Ironically the space environment is better in a lot of respects than the testbed environment.) So, any high contrast technology development must make significant allowances for testbed environment and equipment upgrades.

3.4 Summary of PIAA technology readiness

The table below is a summary of this section along with perceived readiness and risks associated with each element. (Color coded from red to green.)

Component	Readiness	Percieved Risk	Approach
Dichroics	performance in high contrast regime not yet known	not known whether modern dichroic technology is good enough	Multi-channel coronagraphic tests, analysis to choose the best number of wavelength channels
Wavefront control system	$2x10^{-7}$ demonstrated for PIAA, $5x10^{-10}$ for the BLC coronagraph at 4 l/D with one DM	contrast stability issues, broadband control, size of system	WFC algorithm refinement; MEMS DM testing, architecture trade studies
PIAA mirrors	$3x10^{-9}$ in 760-840nm according to simulations	meeting surface error requirements	Further polishing at Tinsley. Tuning WFC architecture design to PIAA mirrors quality. Less aggressive PIAA designs.
Apodizer	apodizers validated to $2x10^{-9}$, but with a different coronagraph	two options to mitigate risk: masks on glass or new designs on free-standing apodizer	Design of star-shaped free-standing apodizer. Better apodizer substrate. Laboratory validation.
LOWFS	demonstrated at Subaru to within a factor of 2-4 of what's needed for 10^{10} contrast	no major risks anticipated	Vacuum test needed to validate performance at 10^{10} level
Integrated modeling of WFC with PIAA	algorithms currently under implementation and testing	model accuracy, computing speed,	Further simulations work required to better understand requirements and guide system architecture and control algorithms

4 Facilities

4.1 Subaru telescope coronagraph testbed

The Subaru facility has been testing PIAA for 3 years and has done early prototyping of an integrated PIAA and wavefront control system. It currently uses PIAAgen1 (the first generation of mirrors, made by Axsys) in monochromatic light, a LOWFS, a single 32x32 MEMS DM, and an actively controlled thermal enclosure stabilized to a few mK. At present, the level of activity at the Subaru testbed is being ramped down and most of the activity is being transferred to Ames. However, it will still be available on a part-time basis if needed.

4.2 Ames Coronagraph Testbed

The Ames testbed has been in operation for about a year and is dedicated to PIAA testing. It is also an air testbed, designed to be highly flexible and reconfigurable. It has more resources and staff than the Subaru testbed and is essentially a successor to the Subaru testbed. Currently it uses a passive thermal enclosure but an active one is being made. The goals of the Ames testbed are to study the feasibility of MEMS DMs with high-contrast (and thus potentially enable significant size reductions of the instrument), explore architecture trade-offs, and study dichroics, and then submit the best and optimal designs and technologies to be tested in HCIT in vacuum.

4.3 High Contrast Imaging Tested (HCIT)

The HCIT at JPL is a mature state-of-the art testbed in vacuum and a leader in contrast demonstrations. It is testing a variety of coronagraphs but is expected to dedicate between 20 and 40% of its time to PIAA in the next several years. It mainly operates in broadband light, uses Xinetics DMs (larger than MEMS DMs), and is about to start tests on PIAAgen2.

5 Program Plan

The general strategy is for the Ames testbed to serve as "pathfinder" testbed and explore potentially valuable and sometimes risky alrernatives and new technologies, while HCIT continues on a set and lower-risk milestone track with technologies that have already been validated in air at lower contrast. The Ames testbed is intended to be kept flexible enough to allow changes of architecture while HCIT's milestone track is being followed. After promising alternatives and/or technologies receive sufficient testing at Ames, they will undergo vacuum testing at HCIT.

The main technologies currently identified for testing at Ames are MEMS DMs, architecture studies of wavefront control, and dichroic tests with multiple channels. In the meantime, HCIT will pursue the goal of achieving a deep contrast with PIAAgen2 and already tested technologies and architectures. An abbreviated list of milestones for HCIT and Ames follows:

HCIT Milestones:

- Demonstration of 5×10^{-10} contrast at 2 λ/D in monochromatic light in vacuum
- Demonstration of 5×10^{-10} contrast at 2 λ/D in 5 % broadband light in vacuum
- Demonstration of 5×10^{-10} contrast at 2 λ/D in 2 10% channels
- Demonstration of fine pointing to better than 1mas
- Demonstration of the above while subjected to flight-like dynamic conditions
- Error budget and model validation

Ames Milestones:

- Initial testbed validation (by demonstrating 3×10^{-7} at 2 λ/D in monochromatic light; this is very close to complete with 4×10^{-7} contrast having been demonstrated)
- Validate MEMS DM technology for high contrast (3×10^{-9} at 2 λ/D in monochromatic light) If this is successful, then follow with MEMS DM testing in HCIT

- A switch to broadband operation and validation of all components in broadband down to 3e-7.
- Initial multichannel and dichroic validation (3×10^{-7} at 2 λ/D in two 10% channels)
- Multichannel validation (3×10^{-9} at 2 λ/D in 2 10% channels)
- Tests of different DM architectures and apodizer options as optimal ones are identified through modeling.

This joint PIAA testing effort is expected to take about 4 years and cost approximately $21M total. This number comes from the expectation that the current operating levels for Ames and JPL will continue, which translates to $6M for Ames for 4 years and $15M for HCIT for four years, assuming a 30% level of dedication of HCIT to PIAA. For further details, please see [3,4].

6 References

[1] Guyon O. "Phase-induced amplitude apodization of telescope pupils for extrasolar terrestrial planet imaging," A&A, 404, pp. 379-387 (2003).

[2] Guyon O., Pluzhnik E. A, Kuchner M. J., Collins B., Ridgway S. T., "Theoretical Limits on Extrasolar Terrestrial Planet Detection with Coronagraphs," *Astrophysical Journal* 167, Issue 1, pp. 81-99 (2006).

[3] Levine M., Soummer R., et. al., "Overview of Technologies for Direct Optical Imaging of Exoplanets," submitted to the *Astro2010 technology development white paper* call. (2009).

[4] Guyon O., et. al., "Pupil-Mapping Exoplanet Coronagraphic Observer," submitted to the *Astro2010 request for information.* (2009).

[5] Guyon, O.; Angel, James R. P.; Backman, Dana; Belikov, Ruslan; "Pupil mapping Exoplanet Coronagraphic Observer PECO," Proc. SPIE, Vol 7010, 70101Y (2008). Also see http://caao.as.arizona.edu/PECO/ .

[6] Traub, W., "Planetscope: Exoplanet Characterization from a Balloon Platform," submitted to the *Astro2010 request for information.* (2009).

[7] Ford et al., "TPF-C Flight Baseline Report", 2005, http://planetquest.jpl.nasa.gov/documents/TPFCFB1_Report.pdf

[8] Give'on A., Belikov R., Shaklan S., and Kasdin J., "Closed loop, DM diversity-based, wavefront correction algorithm for high contrast imaging systems," Optics Express, Vol. 15, Iss. 19, pp. 12338-12343, 09/2007.

[9] Pluzhnik E. A., Guyon O., Ridgway S. T., Martinache F., Woodruff R. A., Blain C., Galicher R., "Exoplanet Imaging with a Phase-Induced Amplitude Apodization Coronagraph III. Diffraction Effects and Coronagraph Design," *The Astrophysical Journal* 644, Issue 2, pp. 1246-1257. (2006).

[10] Belikov R., Kasdin N.J., Vanderbei R.J., "Diffraction-based Sensitivity Analysis of Apodized Pupil-Mapping Systems," *ApJ* Vol 652, issue 1, pp. 833-844, 11/2006.

[11] Belikov R., Give'on A., Kern B., Cady E., Carr M., Shaklan S., Balasubramanian K., White V., Echternach P, Dickie M., Trauger J., Kuhnert A., Kasdin N. J., "Demonstration of high contrast in 10% broadband light with the shaped pupil coronagraph," *Proc SPIE* 6693, 08/2007.