Detecting and Characterizing Exoplanets with a 1.4-m space telescope: the Pupil mapping Exoplanet Coronagraphic Observer (PECO)

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ABSTRACT

The Pupil-mapping Exoplanet Coronagraphic Observer (PECO) mission concept uses a coronagraphic 1.4-m space-based telescope to both image and characterize extra-solar planetary systems at optical wavelengths. PECO delivers 10^{-10} contrast at 2 λ/D separation (0.15") using a high-performance Phase-Induced Amplitude Apodization (PIAA) coronagraph which remaps the telescope pupil and uses nearly all of the light coming into the aperture. For exoplanet characterization, PECO acquires narrow field images simultaneously in 16 spectral bands over wavelengths from 0.4 to 0.9 μm, utilizing all available photons for maximum wavefront sensing and sensitivity for imaging and spectroscopy. The optical design is optimized for simultaneous low-resolution spectral characterization of both planets and dust disks using a moderate-sized telescope. PECO will image the habitable zones of about 20 known F, G, K stars at a spectral resolution of R≈15 with sensitivity sufficient to detect and characterize Earth-like planets and to map dust disks to within a fraction of our own zodiacal dust cloud brightness. The PIAA coronagraph adopted for PECO reduces the required telescope diameter by a factor of two compared with other coronagraph approaches that were considered for Terrestrial Planet Finder Coronagraph Flight Baseline 1, and would therefore also be highly valuable for larger telescope diameters. We report on ongoing laboratory activities to develop and mature key PECO technologies, as well as detailed analysis aimed at verifying PECO's wavefront and pointing stability requirement can be met without requiring development of new technologies.

Keywords: Coronagraphy, Adaptive Optics, Space Telescopes, Exoplanets

1. INTRODUCTION

Thanks to indirect detection techniques (radial velocity, transits, microlensing), the list of known exoplanets is rapidly growing in numbers and now starts to include rocky planets. Direct imaging of these planets is essential to characterize their athmosphere, constrain their physical and orbital properties, and understand in which environment they evolve. Direct imaging can enable spectral characterization of potentially habitable planets and identify "biomarkers".

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In this paper, we present the result of the Pupil mapping Exoplanet Coronagraphic Observer (PECO) mission concept study. PECO is sized at 1.4-m diameter optical space telescope equipped with a coronagraph and designed to fit within the cost envelope of "probe-class" NASA missions.

The Pupil-mapping Exoplanet Coronagraphic Observer (PECO) mission concept is a 1.4-m diameter off-axis space-based coronagraphic telescope designed to both image and characterize extra-solar planetary systems at optical wavelengths. PECO delivers 10^{-10} contrast at the second Airy ring (0.15" radius) using a high-performance Phase-Induced Amplitude Apodization coronagraph (PIAA). The PIAA coronagraph remaps the telescope pupil and uses nearly all of the light coming into the aperture to achieve the full diffraction-limited resolution of the unvignetted aperture. This efficient coronagraphic approach offers optimal science return for a given aperture size. PECO can therefore address some of the key science goals of previous mission designs that had planned to use larger telescopes but with less efficient coronagraphs (e.g., Terrestrial Planet Finder's Flight Baseline 1). Most importantly, our study shows that detection and characterization (low resolution spectroscopy) of planets as small as Earth in the habitable zones of nearby stars is possible even with PECO's 1.4-m aperture. In addition to the use of the high performance PIAA coronagraph, PECO achieves its high sensitivity by simultaneously collecting all photons from 400nm to 900nm in 16 science bands and devoting a large amount of exposure time and many revisits to a select number of high-priority targets.

Design and analysis work performed during our study quantified PECO's pointing and wavefront stability requirements. Solutions that meet these requirements have been defined and evaluated. Key technologies required for PECO have been identified and are actively in testing and development: PIAA coronagraph system-level configuration, broadband wavefront control, pointing control, system modeling for on-orbit performance verification, and flight-qualification of EMCCD detectors. The 1.4-m telescope diameter adopted for the PECO study is driven by the cost envelope of a medium scale mission rather than technology. Much of the design and analysis that went into PECO could be readily applied to a larger, more expensive telescope, resulting in enhanced science return.

PECO design choices and its high performance PIAA coronagraph are described in §2. The PECO implementation is described in §3 and is designed make optimal use of stellar photons for science and continuous wavefront sensing during observations. We discuss in §4 how PECO's wavefront accuracy requirements are met. Finally, in §5, we discuss recent progress in laboratory tests of PECO's coronagraph architecture. We note that PECO's science performance is presented in a separate paper in this volume.[1]

2. HOW TO IMAGE EARTHS / SUPEREARTHS WITH A 1.4M TELESCOPE ?

2.1. MAIN ARCHITECTURE CHOICES

PECO's science goals are to (1) image and characterize rocky planets in the habitable zones of ≈20 nearby stars, (2) image and characterize a large sample of giant planets and (3) map exozodiacal disks around nearby stars. Detailed science performance are presented in a separate paper[1] along with a Design Reference Mission planning science observations. This work shows that SuperEarths (assumed to be twice the diameter of Earth) can be imaged in the habitable zones of ≈ 20 nearby stars. PECO's ability to probe habitable zones of nearby stars to this sensitivity level is enabled by three main design choices which guide the optical design and mission design:

- **High throughput.** PECO's instrument uses a high throughput coronagraph, described in §2.2 along with an optical design which uses dichroics to simultaneously capture light between 0.4μm and 0.9μm.
- **Small inner working angle.** PECO's PIAA coronagraph, described in §2.2, offers a 2 λ/D inner working angle (IWA), allowing PECO to image the habitable zones of main sequence stars at up to 5 to 10pc, depending on stellar luminosity and wavelength. PECO's blue channels offer the best IWA and are therefore essential for identification and orbit determination of previously unknown planets.
- **Observation time.** PECO devotes a large fraction of its 3-yr mission to the observation of 20 high priority targets, which are the stars for which it has the sensitivity to image a SuperEarth in the habitable zone. These stars are revisited at least 10 times to maximize detection probability and minimize orbit uncertainties and possible confusion with other planets or exozodi structures.

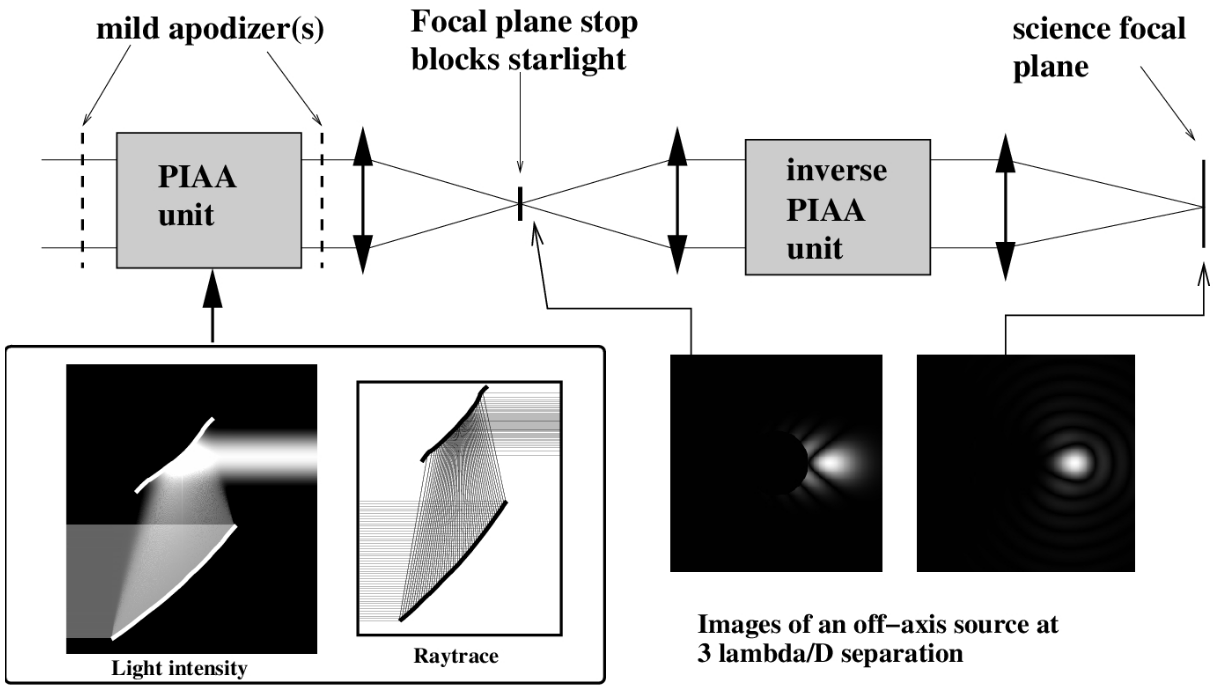

Figure 1. Schematic representation of the PIAAC. The telescope light beam enters from the left and is first apodized by the PIAA unit. Mild apodizer(s) are used to perform a small part of the apodization, and are essential to both mitigate chromatic diffraction propagation effects and allow for the design of "friendly" aspheric PIAA mirrors. An high contrast image is then formed, allowing starlight to be removed by a small focal plane occulting mask. An inverse PIAA unit is required to remove the off-axis aberrations introduced by the first set of PIAA optics.

2.2. PIAA CORONAGRAPH

PECO's Phase-Induced Amplitude Apodization (PIAA) coronagraph efficiently suppresses stellar light while preserving most of the planet's light. A detailed description of this coronagraph technique can be found in previous publications,[2–9] and we briefly summarize in this section the principle and performance of PIAA-type coronagraphs.

As shown in Figure 1, in a PIAA coronagraph, the telescope beam is apodized by two aspheric mirrors which reshape the telescope beam. While a single aspheric mirror is sufficient to transform the top-hat illumination pattern of the telescope into a gaussian-like profile, the second mirror is necessary to re-collimate the output beam. The edges of an apodization profile suitable for high contrast imaging are very dark, and it would be very challenging to manufacture PIAA M1 mirror to project such a dark edge on PIAA M2: the surface curvature at the outer edge of PIAA M1 would need to vary rapidly over a small distance. The apodization is therefore shared between the aspheric mirrors (which perform most of the apodization) and conventional apodizer(s) which can be located before or after the PIAA mirrors. In addition to making PIAA M1 manufacturable, sharing the apodization with a conventional apodizer also greatly improves the chromaticity of the PIAA coronagraph. Thanks to the apodization, a high contrast image of the star is produced in the coronagraphic focal plane: a small occulting mask can therefore block starlight while having little effect on off-axis sources. The beam shaping performed by the PIAA optics introduces strong off-axis aberrations which limit the useful field of view to about 8 λ/D. The PIAAC shown in Figure 1 therefore includes an inverse PIAA to recover a wider unaberrated field of view in the science focal plane.

Thanks to the lossless apodization performed by the PIAA optics, the PECO coronagraph simulatneously offers high contrast, nearly 100% throughput, small inner working angle and full 360 degree discovery space. At 10^{-10} contrast, the PIAA inner working angle (IWA), defined as separation at which the throughput is

50% of its maximum, is slightly under 2 λ/D. Designs with more aggressive IWA are possible, but they must overcome chromaticity issues and extreme sensitivity to low order aberrations and stellar angular diameter. The coronagraph throughput is driven by how much apodization is offloaded to the mild apodizer(s). To keep diffractive chromatic aberrations small and the PIAA optics manufacturable, the PIAA system throughput is therefore about 90%, without including losses in reflective coatings on the mirrors. This high throughput is essential for both science (exoplanets are faint) and wavefront control (minimizes the time necessary to measure wavefront aberrations). Angular resolution, which is preserved by the PIAA coronagraph, is also very important to minimize the amount of zodiacal and exozodiacal light that is mixed with the planet's image, to reduce risks of confusion between several planets, to improve the astrometric precision for the planet's orbit, and to provide sharp images of the exozodiacal cloud.

3. PECO ARCHITECTURE AND IMPLEMENTATION

3.1. OVERVIEW

The baseline concept for PECO is a 1.4m off-axis telescope operating at room temperature. The flight system uses an operational Spitzer-type spacecraft. The mission will last three years, with an option for extension to five years. Key features of this design are the PIAA coronagraph system for diffraction suppression, active wavefront control, photon counting focal plane science detectors, extremely low vibration and high pointing stability (< 10 mas rms for OTA, < 1 mas rms within the instrument). The total system mass is 1727 kg with 20% contingency and the power is 1020 W with 25% contingency. In order to meet the desired wavefront stability requirements, the design uses a drift-away Heliocentric orbit, in conjunction with an internal thermal control system. PECO will be launched inside an Atlas V, 4m fairing. The ground system uses the Deep Space Network (DSN) and heritage equipment, processes, and procedures. The flight system is controlled from the Mission Operations Center (MOC) at LMSSC in Denver, and the Science Operations Center (SOC) at IPAC, JPL.

3.2. OPTICAL DESIGN

The PECO science instrument is designed to take full advantage of the high throughput and small IWA of the PIAA coronagraph. PECO has four parallel coronagraph channels to allow simultaneous acquisition of all photons from 0.4 to 0.9μm. A functional block diagram of the PECO instrument is shown in the left part of Figure 3. After emerging from the beam compressor optics following the secondary mirror, the light is split by dichroics into four nearly identical channels differing only in the physical size of the focal plane mask, the plate scale at the science detector, and the prescription of the pupil reimaging hyperbolas (OAH) necessary to locate the pupil on one of the two deformable mirrors which also serves as a fine guiding mirror. The right size of the Figure depicts the optical design of the instrument for one of these channels. The wavefront control subsystem consists, in each spectral channel, of two deformable mirrors (required for correction in a 360 deg field around the star) and a coronagraphic low order wavefront sensor[10] for accurate measurement of pointing errors and low order aberrations. The two DMs per channel provide the degrees of freedom to correct both phase and amplitude errors in the pupil[11] so that the primary mirror quality requirements do not exceed those already proven for the Hubble Space Telescope. This configuration also provides some redundancy against actuator failure. A set of two aspheric PIAA mirrors (PIAA M1 and M2 on Fig. 3) and a conventional pupil apodizer are used in each channel to fully apodize the telescope beam. The DMs are placed upstream of the PIAA optics allowing them to correct a dark hole extending to roughly 20 λ/D, or about 1.6 arcsec in the visible. An off-axis parabola (OAP3) focuses the apodized beam onto a coronagraph mask (labeled "Mask/LOWFS" in Fig. 3) that blocks the central beam and reflects an annular beam extending to 2 λ/D to the LOWFS camera (not shown in the Figure). A simpler, lower quality inverse PIAA system (Inv. PIAA M1 and M2 in Fig 3) reverses the coma-like aberration in the beam to form a sharp image of the planet across the field.[2,4,5,12] Before reaching the detector, the beam is split into two linear polarizations by a Wollaston prism and four spectral channels with dichroics (these optics are not shown in Fig. 3). In all there thirty two separate images formed on the detectors in the four channels. Figure 3-3: Optical Design of one of the four spectral channels in the PECO science instrument

PECO is thus designed to make optimal use of incoming photons, with a large spectral coverage (0.4 μm to 1.0 μm). Maximizing the total number of photons transmitted to the detectors is essential for both science and wavefront control:

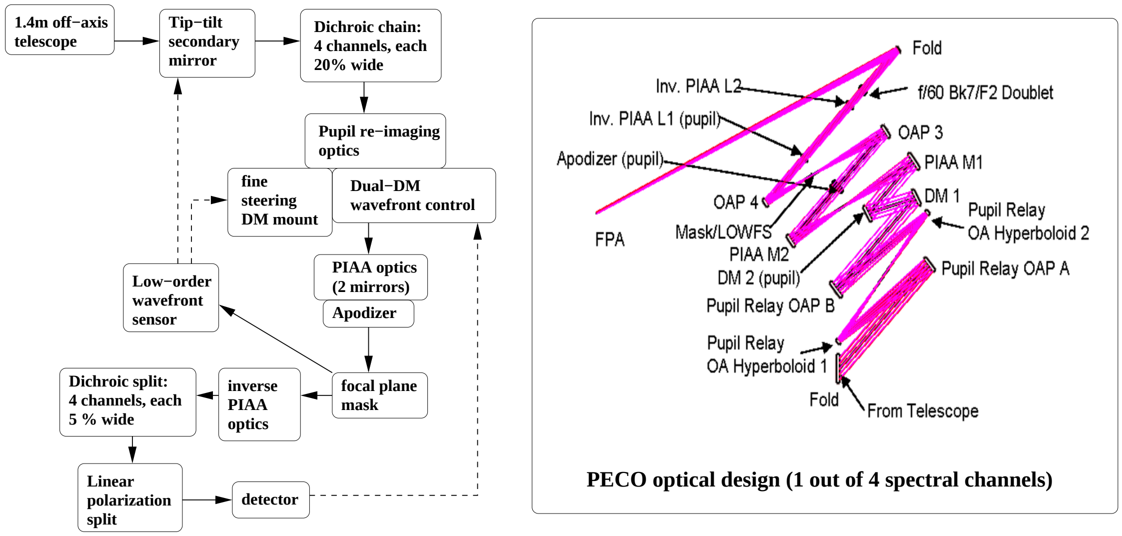

Figure 2. Block diagram of the PECO optical layout. Solid arrows show the light path; dashed arrow show wavefront control signals. The 1.4-m off-axis telescope's beam is apodized by the PIAA mirrors. A set of dichroics splits light in 4 spectral channels. The optical layout within one of these spectral channels is shown in the right part of the figure.

- Exoplanets are faint, and the total observing times required for detection with a 1.4-m telescope are long (typically a day per target) even in broadband.
- With more photons detected per unit of time, the wavefront control system is better able to track and correct aberrations.

The number of PECO spectral channels (four in the baseline concept) is driven by the spectral bandwidth over which high contrast can be achieved, and can be traded against wavefront control agility (for example, number and location of DMs in each channel).

4. PECO WAVEFRONT CONTROL

4.1. POINTING CONTROL

Target acquisition is performed in two steps with the reaction wheels:

- Using the star tracker signal only, the spacecraft is pointed to a 1 arcsec absolute accuracy. The Lockheed Martin AST 301 autonomous star tracker currently flying on Spitzer has demonstrated performance better than required, achieving 0.4 arcsec over 24 hours over a 5 degree field of view.
- The LOWFS detector is used in a wide field mode to center the star within the high sensitivity 0.1arcsec region of the LOWFS. In this mode, <1% of the starlight is reflected by the glass substrate on which the focal plane mask is deposited, which is enough light for acquisition and centering of the star.

The instrument pointing tolerance during observations is no more than 1% of the diffraction width (i.e. ¡1 mas). The PECO strategy to meet this stability is fourfold:

- Operate in a very stable environment far from Earth (heliocentric orbit).
- Eliminate vibration coupling from the reaction wheels by using a hexapod isolation system under each reaction wheel and design the OTA and optical mounting for stiffnes.

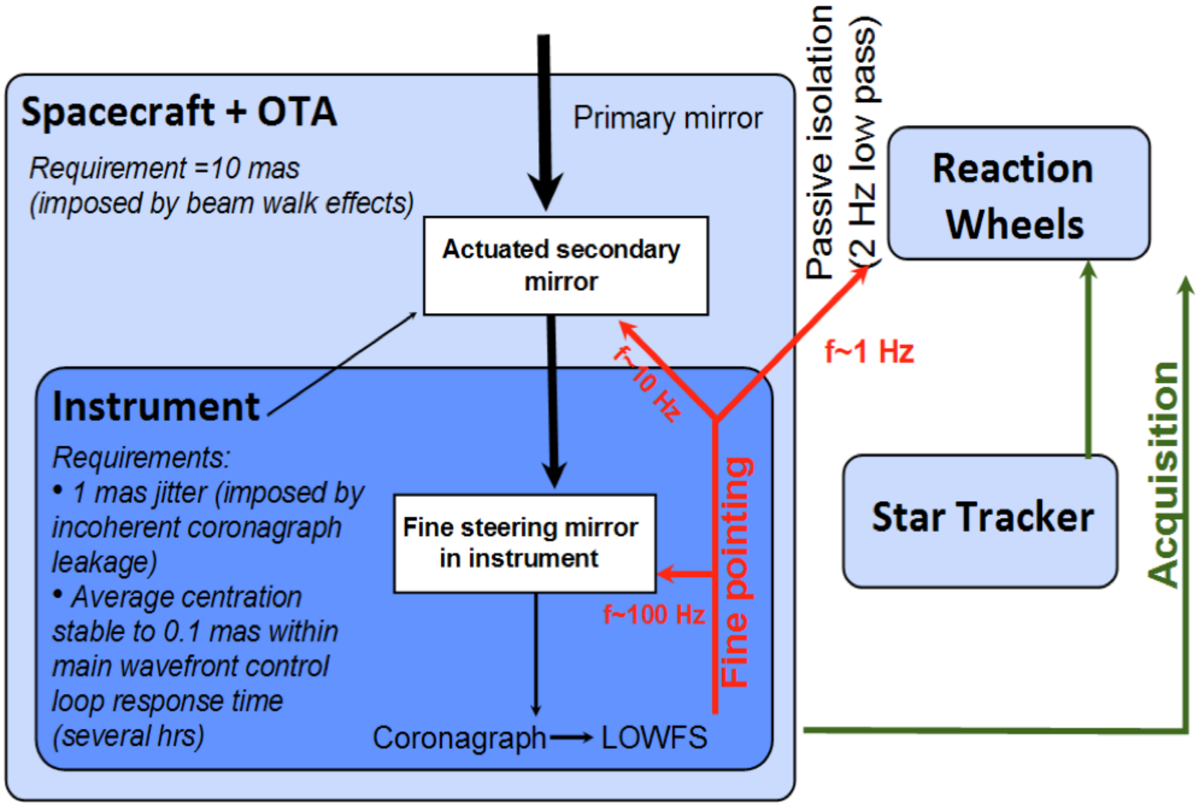

Figure 3. Conceptual representation of the PECO optical layout. The 1.4-m off-axis telescope's beam is apodized by the PIAA mirrors. A set of dichroics splits light in 4 spectral channels. The optical layout within one of these spectral channels is shown in this figure. See text for details.

- Derive an accurate control signal from the bright target star image reflected by the coronagraphic stop. The LOWFS measures sub-mas pointing errors at >100 Hz.
- Use the actuated telescope secondary mirror (momentum compensated) and fine steering the DMs conjugated to the pupil within the instrument to meet the tight instrument pointing tolerance (1 mas) with a relaxed OTA pointing requirement of 10 mas. Using HST as a bench-mark (3 mas pointing stability in LEO), our models show we will meet the OTA pointing requirement.

In addition to the pointing jitter requirement described above, the time-averaged position of the star image over the focal plane coronagraph mask should be stable (or known) to within 0.1mas over a period of a few hours to avoid coherent mixing of starlight leaks with residual speckles. The zero point of the LOWFS must therefore be extremely stable. PECO's LOWFS meets this requirement because the measurement is referenced to the dark non-reflective spot at the center of the focal plane mask, which has been demonstrated in the laboratory to 0.1mas precision.[10]

4.2. WAVEFRONT STABILITY AND CONTROL

Each spectral band includes a separate inverse PIAA to maintain high image quality over the full extent of the "dark hole" produced by the wavefront control system. Thanks to the small spectral coverage of each band and the location of the inverse PIAA systems (after the coronagraphic mask, where optical quality requirements are considerably relaxed), compact refractive optics can be used for the inverse PIAA.

The goal of the wavefront correction algorithm is to command the DM to cancel out mid-spatial frequency wavefront errors, manifested as scattered light (speckles) and measured in the science focal plane. The DMs are commanded by a phase diversity signal to modulate the speckle intensity, allowing recovery of both amplitude and phase of the speckles without being affected by the incoherent planet light and the zodiacal light. The Electric Field Conjugation (EFC) algorithm[13] baselined for PECO, has been used on the High Contrast Imaging Testbed (HCIT) at JPL, using one DM and a band-limited coronagraph, achieving contrasts of 6 10^{-10} in 10% broad light at 4λ/D. Similar approaches have already been successfully used as close as 2 λ/D in the Subaru PIAA testbed. Wavefront sensing is achieved by monitoring scattered light in the PECO science frames, which are acquired with photon-counting CCD read every few seconds. The DMs are continuously updated to correct for varying wavefront aberrations and provide the phase diversity signal necessary to measure the complex amplitude of starlight scattered by aberrations. Signals from all spectral channels can be added to improve wavefront sensing sensitivity in order to optimally track time-variable aberrations which are expected to be mostly achromatic.

For PECO we baseline the Xinetics deformable mirrors (DM). The PECO design requires eight 48x48mm DMs with a 1 mm pitch. This design is identical to the ones being currently tested in the JPL HCIT and which have already been proven to TRL 6 to PECO specifications. No further DM technology work is required; however the program intends to make use of other emerging DM technologies such as higher actuator count DMs and MEMS (e.g., Boston Micromachines) should they be ready by mission start. These are being actively pursued by other exoplanet missions and offer the promise of being more compact, lighter and less expensive.

Thermal disturbances are generated when the telescope sun angle is changed (pointing to a new target). Since the instrument can only compensate for thermal aberrations through active wavefront control if they are sufficiently stabilized, high contrast observations must be delayed after each pointing. PECO thermal modeling shows that this delay is a few hours for large pointing offsets. The impact on PECO's observing efficiency is therefore small, and can be further mitigated by careful scheduling to minimize large changes in Sun angle.

A detailed finite element model (FEM) of the PECO system, was generated to asess optical stability when subjected to reaction wheel jitter and thermal gradients and to perform a modal assessment. The PECO structure is a stiff, efficient design. The 1st and 2nd elastic modes, baffle bending, are very high at 16.2 and 16.4 Hz. The next modes, telescope scissoring, are at 26.5 and 28.8 Hz. To minimize optical jitter each of the four Goodrich B-type reaction wheels is supported by a 5-axis, 2 Hz hexapod passive isolation system. Line of sight jitter can be kept well below the 10 mas requirement by operating the wheels in an intermediate range (500 - 1200 RPM) which avoids isolation system resonance as well as minimizing resonance of the optics. The relative motions of the optics are extremely small. Temperature gradients from the thermal analysis were applied to the optical telescope and instrument bench. Analyses showed that the gradients can be kept extremely small by precise thermal control. The resulting deflections of the optical elements in the telescope and instrument are well below the required 3 nm and 5 nrad stability requirements. Overall, the analyses show that the PECO design meets its stability margin to carry out its robust science mission.

5. CORONAGRAPH TECHNOLOGY DEVELOPMENT STATUS

Demonstration of the starlight suppression coronagraph system to reach contrast levels of 10^{-9} to 10^{-10} in broadband light is required for Earth imaging. The starlight suppression system consists of the coronagraph optics, deformable mirrors and wavefront control algorithms. Coronagraph model validation is also required as an indication that the physics of starlight suppression including diffraction and polarization are well understood and can be extrapolated to a flight mission error budget. The PIAA Starlight Suppression System consists of the four subsystems described below.

5.1. PIAA coronagraph optics design and manufacturing

At the core of the PECO coronagraph are the PIAA mirrors which are a pair of aspheric high quality optics which perform the apodization. Tinsley, under contract to NASA ARC has recently delivered a pair of high fidelity PIAA-generation 2 mirrors to the NASA JPL High Contrast Imaging Testbed for testing of a PIAA coronagraph to broadband milestone levels. These mirrors are shown in Figure 4.

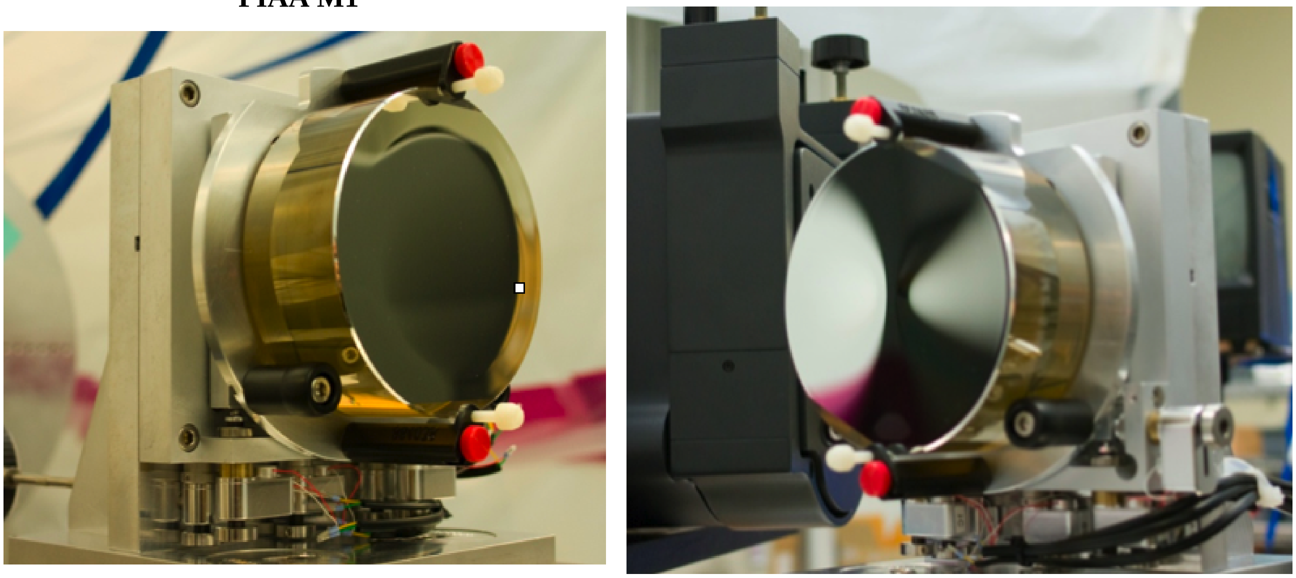

Figure 4. PIAA generation 2 mirrors.

5.2. Ongoing PIAA laboratory testing

Starlight suppression with PIAA coronagraph was first tested in the Subaru Telescope laboratory. The Subaru testbed was designed to validate PIAA at intermediate contrast for preliminary prototyping and performance validation for use on ground-based telescopes. Results obtained in this testbed are shown in Figure 5. The testbed achieved a 2.27 10^{-7} raw contrast between 1.65 λ/D (inner working angle of the coronagraph configuration tested) and 4.4 λ/D (outer working angle). Through careful calibration, it was possible to separate this residual light into a dynamic coherent component (turbulence, vibrations) at 4.5 10^{-8} contrast and a static incoherent component (ghosts and/or polarization missmatch) at 1.6 10^{-7} contrast. Pointing errors are controlled at the 10^{-3} λ/D level using a dedicated low order wavefront sensor. While not sufficient for direct imaging of Earth-like planets from space, the 2.27 10^{-7} raw contrast achieved already exceeds requirements for a ground-based Extreme Adaptive Optics system aimed at direct detection of more massive exoplanets. Over a 4hr long period, averaged wavefront errors were controlled to the 3.5 10^{-9} contrast level (Figure 5). This result is particularly encouraging for ground based Extreme-AO systems relying on long term stability and absence of static wavefront errors to recover planets much fainter than the fast boiling speckle halo.

The Subaru Telescope PIAA testbed activity has now ended and efforts at Subaru Telescope are focused on deploying already validated technology on the ground-based telescope. PIAA technology is now actively developped in two laboratories which are more capable than the Subaru lab was:

- The NASA Ames Research Center PIAA coronagraph laboratory is a highly flexible testbed operating in air. It is dedicated to PIAA technologies and is ideally suited to rapidly develop and validate new technologies and algorithms. It uses MEMS-type deformable mirrors for wavefront control
- The NASA JPL High Contrast Imaging Testbed is a high stability vacuum testbed facility for coronagraphs. PIAA is one of the coronagraph techniques tested in this lab, which provides the stable vacuum environment ultimately required to validate PIAA for flight.

Recent PIAA results obtained at these testbeds are given in other papers within this volume.[14,15]

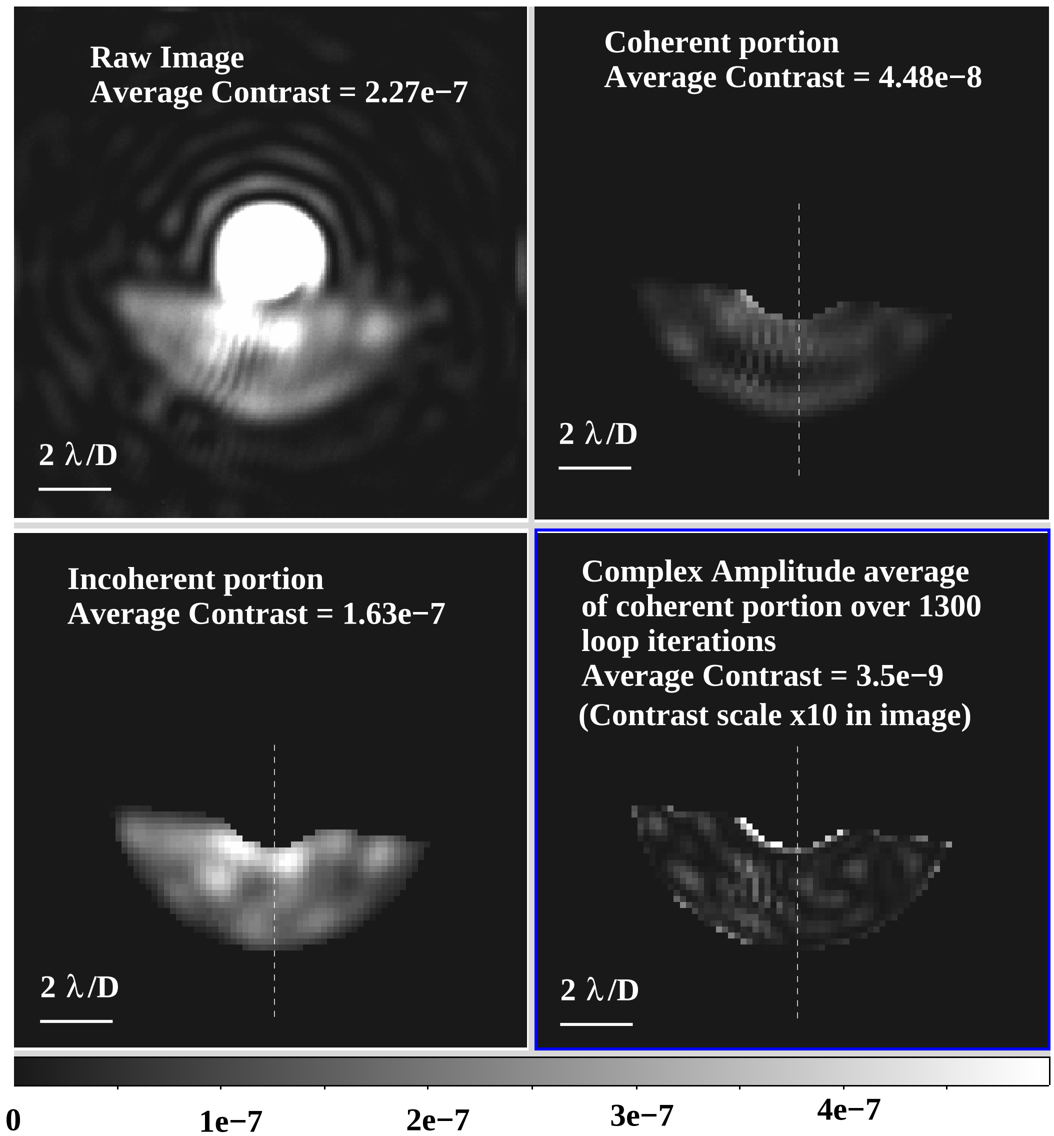

Figure 5. Laboratory results from the PIAA laboratory testbed at Subaru Telescope.

ACKNOWLEDGMENTS

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