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The Pupil Mapping Exoplanet Coronagraphic Observer (PECO)

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Abstract. The Pupil-mapping Exoplanet Coronagraphic Observer (PECO) is a mission concept using 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. PECO's heliocentric drift-away orbit provides a stable thermal environment for wavefront control. 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 $\sim$15 with sensitivity sufficient to detect and characterize Earth-like planets and to map dust disks as small as a fraction of our own zodiacal dust cloud brightness. An active technology development program, including coronagraph and wavefront control laboratory demonstrations at NASA Ames and NASA JPL, is currently addressing key technology needs for PECO.

1. Overview of PECO Mission Concept

PECO is a 1.4-m off-axis telescope operating at room temperature. 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). 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.

The PECO science instrument is designed to take full advantage of the high throughput and small inner working angle (IWA) of the PIAA coronagraph. PECO has four parallel coronagraph channels to allow simultaneous

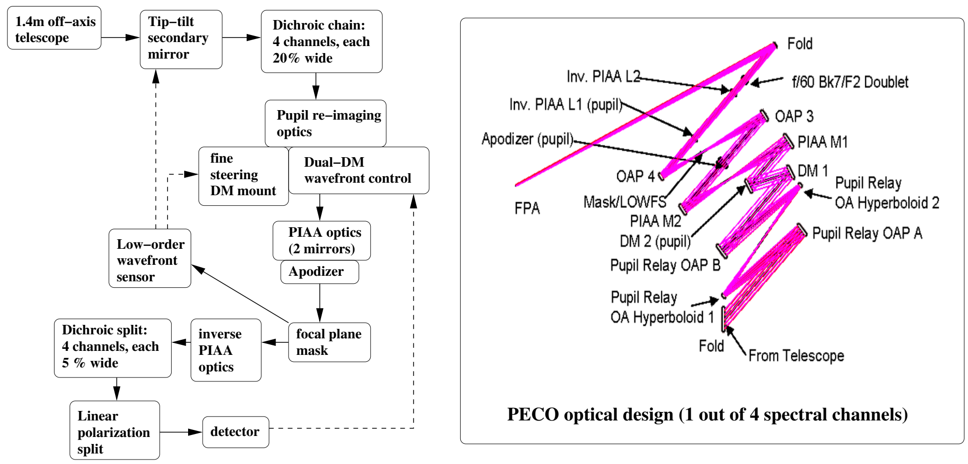

Figure 1. Block diagram of the PECO optical layout. Solid arrows show the light path; dashed arrows show wavefront control signals. The 1.4-m off-axis telescope's beam is apodized by the PIAA mirrors. A set of dichroics splits light in 4 spectral channels. The optical layout within one of these spectral channels is shown in the right part of the figure.

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 1. Light is split by dichroics into four nearly identical coronagraph channels. The right side 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 (DMs; required for correction in a 360 deg field around the star) and a coronagraphic low order wavefront sensor (Guyon et al. 2009a) 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 (Shaklan et al. 2009) so that the primary mirror quality requirements do not exceed those already proven for the Hubble Space Telescope. A set of two aspheric PIAA mirrors (PIAA M1 and M2 on Figure 1) 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 Figure 1) 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 Figure 1) reverses the coma-like aberration in the beam to form a sharp image of the planet across the field (Guyon et al. 2003; Vanderbei et al. 2005; Guyon et al. 2005; Lozi et al. 2009). 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 Figure 1). In all there are 32 separate images formed on the detectors in the four channels (16 spectral bands x 2 polarizations).

PECO is thus designed to make optimal use of incoming photons, with a large spectral coverage (0.4 μm to 0.9 μm). Maximizing the total number of

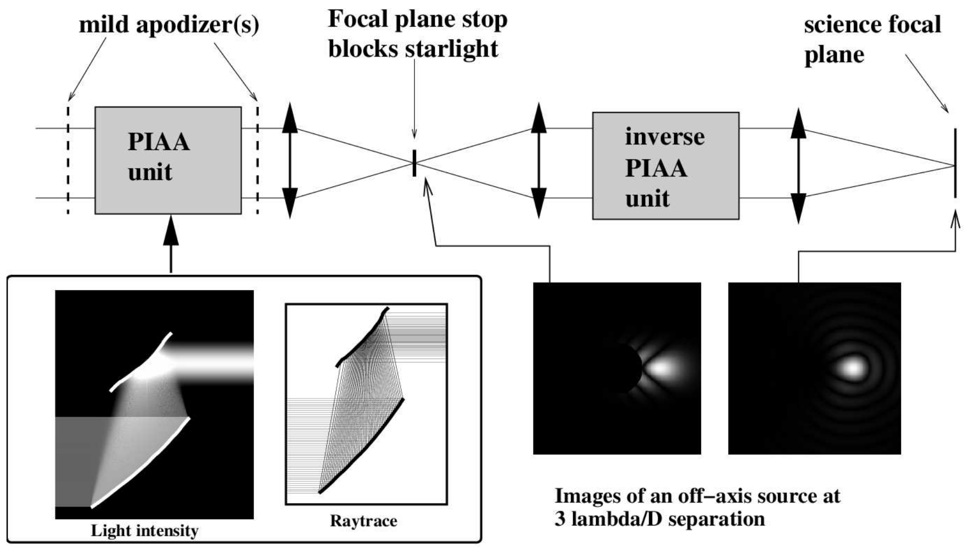

Figure 2. Schematic representation of the PIAAC. The telescope light beam enters from the left and is first apodized by the PIAA unit. Mild apodizer(s) are used to perform a small part of the apodization, and are essential to both mitigate chromatic diffraction propagation effects and allow for the design of friendly aspheric PIAA mirrors. A 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.

photons transmitted to the detectors is essential for both science (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) and wavefront control (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).

2. PIAA Coronagraph

PECO's Phase-Induced Amplitude Apodization (PIAA) coronagraph efficiently suppresses stellar light while preserving most of the planet's light. This coronagraph offers simultaneously a high throughput (close to 100%) and a small inner working angle (2 λ/D). A detailed description of this coronagraph technique can be found in previous publications (Guyon et al. 2003; Traub et al. 2003; Guyon et al. 2005; Vanderbei et al. 2005; Martinache et al. 2006; Vanderbei 2006; Pluzhnik et al. 2006a,b), and we briefly summarize in this section the principle and performance of PIAA-type coronagraphs.

The coronagraph architecture is shown in Figure 2. The telescope beam is apodized by two aspheric mirrors which reshape the telescope beam, and a conventional mild apodizer 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 2 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 IWA and full 360 degree discovery space. At 10^{-10} contrast, the PIAA IWA, defined as separation at which the throughput is 50% of its maximum, is slightly under 2 λ/D.

3. Wavefront Control

Pointing: 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 relies on creating a stable environment (heliocentric orbit and vibration isolation of reaction wheels) and deriving an accurate control signal from the bright target star image reflected by the coronagraphic stop (this is done with sub-mas accuracy at >100 Hz). Measurement of pointing error with light reflected from the central focal plane mask has been recently demonstrated in the laboratory to a precision equivalent to 0.1mas on PECO (Guyon et al. 2009a).

Control of mid-spatial wavefront aberrations: 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. 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. The Electric Field Conjugation (EFC) algorithm (Giveón et al. 2007) 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.

4. Coronagraph System Technology Development

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.

Ongoing PIAA laboratory testing: Starlight suppression with PIAA coronagraph was first tested in the Subaru Telescope laboratory with a monochromatic testbed operated in air. 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) (Guyon et al. 2010). 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 (Belikov et al. 2009, Greene et al. 2009). 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 (Kern et al. 2009).

5. Expected Science Return

The efficient coronagraphic approach adopted for PECO 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.

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. PECO devotes a large fraction of its 3-year mission to the observation of 20 high priority targets, which are the stars for which it has the sensitivity to image a super-Earth 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.

PECO's PIAA coronagraph offers a 2 λ/D 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.

Detailed performance simulations have been performed to identify stars around which PECO could detect planets of different types (Cahoy et al. 2009).

We assume here that a planet is detectable if a SNR of 5 can be reached within 12 hr exposure time at a spectral resolution of 5 at λ=550nm along 20% of its orbit. With this detection limit, simulations show that:

- Super-Earths (assumed to be twice the diameter of Earth) can be imaged in the habitable zones of $\approx$ 20 nearby stars;
- Earths can be detected around 9 stars;
- At least 13 known radial velocity planets can be imaged;

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.

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