Direct imaging of exoplanets

The Pupil Mapping Coronagraph Observer (PECO)

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Subaru Telescope
Exoplanets

How many planets around other stars?
How do they form, evolved?
Mass, size, composition?
Rocky planets with atmospheres?
What is the atmosphere composition?
Weather, rotation period?
Could have life evolved on other planets?
Intelligent life somewhere else?
Current status of exoplanet discoveries

"Planet Semi-Major Axis" vs "Planet Mass" (340)

"Year of discovery" vs "Planet Mass" (347)
Indirect detection techniques

Doppler Shift due to Stellar Wobble

Graphs showing RV (km s⁻¹) vs. time and O-C (m s⁻¹) vs. time for 51 Peg and ELODIE.
Indirect detection techniques
Ground-based imaging (Near-IR, with Adaptive Optics)

- Most sensitive to outer young planets: very complementary to Radial Velocity, astrometry, transits -> important for testing planetary formation models (core accretion, gravitational collapse of disk instabilities ?)
- Study planet formation by imaging disks and planets
- Current limitation: mass/age/luminosity relationship (cooling rate) poorly known
- NEED to get closer in to the star / higher contrasts for overlap with radial velocity planets -> constrain mass/age/luminosity models
- NEED to get closer in/higher contrasts to capture REFLECTED light -> “old” planets can then be detected around nearby stars (known targets from radial velocity)
- NEED to increase sample size (currently ~5, possibly most of them are “exceptions” to the rule) with spectral characterization

Space-based imaging (Visible, extremely high high contrast)

- Characterization (spectroscopy) of Earth-mass planets in habitable zone
- Simultaneous imaging of exozodi cloud, massive and rocky planets
- understanding planetary systems formation & evolution
- Planetary atmospheres, physical properties

Kalas et al. 2008

Marois et al. 2008

Lagrange et al. 2009
- Orbit
- Atmosphere composition
- Continents vs. Oceans?
- Rotation period
- Weather patterns
- Planetary environment:
  - Planets + dust
- Venus & Mars spectra look very similar, dominated by CO2
- Earth spectra has CO2 + O3 + H2O + O2 + CH4
  - Together, these gases indicate biological activity
Red edge spectral feature

- Red edge in Earth spectra due to plants, and remotely detectable

Fig. 7.—Earth’s observed reflectance spectrum, at visible and near-infrared wavelengths, created from a composite of the data in this paper (0.8–2.4 μm) and the data presented in Paper I (0.5–0.8 μm). The strongest molecular signatures are indicated, as are the wavelengths where Rayleigh scattering and vegetation reflection are most significant.

Turnbull et al. 2006
Pupil mapping Exoplanet Coronagraphic Observer

http://caao.as.arizona.edu/PECO/

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### Mission Study Manager:
Marie Levine – NASA Jet Propulsion Laboratory - California Institute of Technology

### Science Studies (Lead: NASA Ames Research Center)

<table>
<thead>
<tr>
<th>Principal</th>
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<tbody>
<tr>
<td>K. Cahoy (NASA ARC) – Co-I</td>
<td>Design Reference Mission</td>
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<tr>
<td>J. Kasting (Penn State) Co-I</td>
<td>Terrestrial planets: spectral characterization</td>
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<tr>
<td>M. Marley (NASA ARC) – Co-I</td>
<td>Giant planets: spectral characterization, modeling</td>
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<td>M. Meyer (U of A) – Co-I</td>
<td>Planetary systems formation, evolution</td>
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<td>W. Traub (JPL-Caltech) – Co-I</td>
<td>Science plan</td>
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<td>S. Ridgway (NOAO) – Co-I</td>
<td>Science advisor</td>
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<tr>
<td>D. Backman (SOFIA) – Collaborator</td>
<td>Exozodiacal dust</td>
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<tr>
<td>G. Schneider (U of A) – Collaborator</td>
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<tr>
<td>M. Tamura (NAOJ) – Collaborator</td>
<td>Planetary systems formation</td>
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<td>N. Woollf (U of A) - Collaborator</td>
<td>Characterization of planetary atmospheres, habitability</td>
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### Architecture Studies (Lead: Co-I S. Shaklan – NASA Jet Propulsion Laboratory - Caltech)

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<tr>
<td>A. Give’ on (JPL-Caltech) – Co-I</td>
<td>WFS&amp;C algorithms for Architecture studies and HCIT test demo</td>
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<td>E. Jordan (JPL-Caltech) – Co-I</td>
<td>Systems Engineering</td>
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<tr>
<td>R. Vanderbei (Princeton) – Co-I</td>
<td>Coronagraph architecture and analysis</td>
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<tr>
<td>R. Belikov (NASA ARC) – Collaborator</td>
<td>Coronagraph architecture and analysis</td>
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<td>J. Kasdin (Princeton) – Collaborator</td>
<td>Architecture</td>
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<tr>
<td>E. Serabyn (JPL-Caltech) – Collaborator</td>
<td>Wavefront sensing and speckle nulling</td>
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### Mission Technology (Lead: Co-I Marie Levine – NASA JPL w/ contributions from NASA ARC)

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<tr>
<td>R. Angel (U of A) – Co-I</td>
<td>Technology development, wavefront sensing, primary mirror</td>
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<tr>
<td>D. Gavel (UCSC) – Collaborator</td>
<td>Characterization of MEMS type DMs for PECO</td>
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<tr>
<td>M. Shao (JPL-Caltech) – Collaborator</td>
<td>MEMS DMs characterization, wavefront sensing &amp; control</td>
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<tr>
<td>J. Trauger (JPL-Caltech) – Collaborator</td>
<td>Xiketics DMs expertise, wavefront sensing &amp; control</td>
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### Mission Implementation (Lead: Co-I D. Tenerelli – Lockheed Martin)

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<tr>
<td>R. Woodruff (LM) – Co-I</td>
<td>PECO instrument design, implementation, cost and technology</td>
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<tr>
<td>R. Egerman (ITT) – Co-I</td>
<td>PECO telescope design, implementation, cost and technology</td>
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NASA-funded Advanced Strategic Mission Concept Study, medium class mission (~$800M cost cap)

High contrast coronagraphic imaging of the immediate environment of nearby stars.

Characterization of planets (including Earths/SuperEarths) and dust in habitable zone

- 1.4m diameter off-axis telescope (sized for medium-class cost cap), 3 yr mission
- drift-away heliocentric orbit for maximum stability
- Uses high efficiency low IWA PIAA coronagraph
- 0.4 – 0.9 micron spectral coverage / R~20, polarimetric imaging
- Active technology development program includes NASA JPL, NASA Ames, Subaru Telescope, Lockheed Martin
Earth/SuperEarths with a medium-class mission?

Yes, if:

- **High throughput** instrument & good detector
  - high throughput coronagraph
  - very high efficiency (~45% of photons from the FULL aperture detected), use dichroics instead of filters
  - combined imaging & spectroscopy
  - photon counting (no readout noise allowed)

- Small **Inner Working Angle** AND full telescope **angular resolution**
  - good coronagraph
  - use blue light for discovery & orbit determination

- Large amount of **observation time** on few targets
  - small sample of the easiest ~20 targets
  - long exposure times & many revisits

- Risks: high exozodi & low Earth frequency
  - broader science case:
    - exoplanetary system architecture
    - extrasolar giant planets characterization
    - exozodi disks imaging - **exozodi level measurement**
PECO driving requirements

- **High Contrast (1e10) from 400nm to 900nm (simultaneously !)**
  
  *Key to achieve sensitivity required for science goals*
  
  - Coronagraph / optical train design: use of dichroics feeding coronagraph channels
  - Wavefront control system needs to have sufficient degrees of freedom to correct wavefront over spectral range

- **Wavefront Stability (A)**
  
  *Wavefront sensing & control response time at 1e10 contrast level is ~mn to ~hr. Any non calibrated WF variation on <hr timescale will seriously affect science return*
  
  - High throughput efficient wavefront sensing to reduce response time
  - Stable telescope, temperature control, low jitter/vibrations
  - Stable drift-away heliocentric orbit, no telescope roll

- **Pointing Stability and knowledge (mas)**
  
  *Key to image planets/disk at small separations AND not get confused with pointing errors*
  
  - Stable orbit / telescope design
  - Multi-stage control
  - High sensitivity sensing of pointing errors
Coronagraph choice is essential

- Coronagraph role is to block starlight and let as much planet light as possible through the system
- Most coronagraph designs are a painful tradeoff between coronagraphic rejection and throughput, inner working angle, angular resolution
Utilizes lossless beam apodization with aspheric optics (mirrors or lenses) to concentrate starlight in a single diffraction peak (no Airy rings).

- high contrast
- Nearly 100% throughput
- IWA ~2 I/d
- 100% search area
- no loss in angular resol.
- achromatic (with mirrors)

Guyon, Pluzhnik, Vanderbei, Traub, Martinache ... 2003-2006
**Figure 3-1:** Useful Throughput of several coronagraphs (adapted from Guyon et al. 2006). OVC = Optical Vortex Coronagraph, VNC = Visible Nuller Coronagraph, BL4 = 4th order Band-Limited Lyot coronagraph, BL8 = 8th order Band-Limited Lyot coronagraph, PSC = Pupil Swapping coronagraph, CPA = conventional Pupil Apodization.
PECO approaches theoretically optimum coronagraph performance

- High performance PIAA coronagraph

- Simultaneous acquisition of all photons from 0.4 to 0.9 µm in 16 spectral bands x 2 polarization axis, combining detection & characterization
  - High sensitivity for science and wavefront sensing
  - Polarization splitting just before detector (helps with exozodi & characterization)

- Wavefront control and coronagraph perform in 4 parallel channels
  - Allows scaling of IWA with lambda
  - Allows high contrast to be maintained across full wavelength coverage
• Conduct a “Grand Tour” of ~20 nearby stars searching for small (Earth & Super-Earth) planets in their habitable zones.
  – Multiple (~10 or more) visits for detection
  – Characterization for ~5 days each to get S/N = 20-30 with ability to measure spectral features
  – exozodi distribution measurement
  – compile with other measurements (RV, Astrometry, ground imaging)

• Study known RV planets, observing them at maximum elongation
  – Detect at least 13 RV planets with single visits at maximum elongation
  – Characterize at least 5 RV planets for ~2-5 days each to get S/N > 30 with ability to measure spectral features

• Snapshot survey of ~100 other nearby stars to study diversity of exozodiacal disks and search for / characterize gas giant planets.
PECO imaging simulations

PECO simulated images used to predict science performance

- Assumes QE x throughput loss = 0.45, given by model of detector QE, instrument optical layout (losses in coatings)
- Assumes exozodi cloud similar to solar
- Takes into account stellar angular size
- Takes into account local zodi (level set by ecliptic latitude of target)
- Instrumental PSF computed for each point of the source (stellar disk, planet, exozodi, zodi): each image requires ~30000 coronagraphic PSFs
- Single visit detection probabilities computed assuming location of planet along its orbit is unknown

**PECO science simulations performed by K. Cahoy, NASA Ames, with input from PECO science team**
Number of Earths detected with PECO scales gracefully with aperture

- Trade study shows number of Earths detected for different telescope diameters
- PECO simulation of Earth-radius planet with Earth albedo in habitable zone of candidate star
- Assumes planet is detectable (SNR=5, R=5) in under 12 hr exposure (vertical line in figure) along 20% of its orbit. Single visit completeness > 20% in 12 hr exposure.
- IWA of 2 lambda/D
PECO can observe an Earth at distance of Tau Ceti

**Left:** a simulation of 24 hr of PECO data showing an Earth-like planet (a=0.2) around Tau Ceti with 1 zodi of exo-dust in a uniform density disk inclined 59 degrees. This is a simulation of λ= 550 nm light in a 100 nm bandpass PECO (1.4-m aperture). Photon noise and 16 electrons total detector noise for an electron multiplying CCD have been added.

**Right:** the PECO image after subtracting the right half from the left half, effectively removing the exozodiacal dust and other circularly symmetric extended emission or scattered light. The Earth-like planet is obvious as the white region on the left, and the dark region on the right is its mirror image artifact.
PECO can easily detect Super–Earths

Trade study shows number of Super-Earths detected for different telescope diameters:

- PECO simulation of 2 x Earth-radius planet with 10 x Earth-mass and Earth-like albedo in habitable zone of candidate star
- Assumes planet is detectable (SNR=5, R=5) in under 12 hr exposure (vertical line in figure) along 20% of its orbit. Single visit completeness > 20% in 12 hr exposure.
- IWA of 2 lambda/D

Can see more targets at shorter wavelengths and larger diameters
Table 4-2: Stars with Earth-like planets in habitable zones (1 AU equiv) easily detectable with PECO.

<table>
<thead>
<tr>
<th>HIP#</th>
<th>dist (pc)</th>
<th>max e(l/V)</th>
<th>*rad (V/D)</th>
<th>SNR(1s,tp)</th>
<th>t20% (s,tp)</th>
<th>Comment</th>
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<tbody>
<tr>
<td>71683</td>
<td>1.3</td>
<td>11.5</td>
<td>0.06</td>
<td>0.84</td>
<td>35</td>
<td>Alf Cen A G2 V, V=0</td>
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<td>71681</td>
<td>1.3</td>
<td>6.6</td>
<td>0.04</td>
<td>0.75</td>
<td>44</td>
<td>Alf Cen B K2 IV, V=1.3</td>
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<td>8102</td>
<td>3.6</td>
<td>2.3</td>
<td>0.01</td>
<td>0.1</td>
<td>2750</td>
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<td>2.2</td>
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<td>Eps Eri K2 V, V=3.7 **</td>
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<td>0.01</td>
<td>0.04</td>
<td>14329</td>
<td>Eta Cas G0 V V=3.5 ***</td>
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<tr>
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<td>7.5</td>
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<td>0.01</td>
<td>0.04</td>
<td>14878</td>
<td>Bet Hyi G0 V, V=2.8</td>
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<tr>
<td>99240</td>
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Table 4-3: Stars with Super-Earth planets in habitable zones (1 AU equiv) easily detectable with PECO.

<table>
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<tr>
<th>HIP#</th>
<th>dist (pc)</th>
<th>max e(l/V)</th>
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<th>SNR(1s,tp)</th>
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NOTE: ** indicates the presence of significant dust (~10 zodi or more) and *** indicates a close multiple star system (preventing high contrast observations) in Tables 4-2 and 4-3.
Known EGPs observable with PECO

List of known Radial Velocity EGPs observable with PECO

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<tr>
<th>Planet Name</th>
<th>Mp (Mjup)</th>
<th>Period (d)</th>
<th>a (AU)</th>
<th>sep''</th>
<th>550nm/D</th>
<th>Dist (pc)</th>
<th>St. Sp T</th>
<th>M*</th>
<th>St. Mag. V.</th>
<th>Pl mag V</th>
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<td>55 Cnc d</td>
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<td>13.5 F8 V</td>
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<td>903</td>
<td>2.04</td>
<td>0.17</td>
<td>2.14</td>
<td>11.8 K2 V</td>
<td>1.4</td>
<td>3.22</td>
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<td>2.11</td>
<td>0.15</td>
<td>1.86</td>
<td>14.0 G0V</td>
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<td>5.1</td>
<td>26.1</td>
<td>4.1E-09</td>
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</tr>
</tbody>
</table>
Shown is a simulation of 24 hrs of PECO data showing the Jovian planet 47 Uma b with 3 zodis of exozodi dust in a uniform density disk inclined 59 deg.

This is a simulation of 550 nm light in a 100 nm bandpass with predicted PIAA performance in the PECO observatory (1.4-m aperture).

Photon noise and 16 electrons total detector noise (for an electron-multiplying CCD) have been added.

This and other RV planets are very easy detections for PECO even in the presence of significant exozodiacal dust, demonstrating that PECO will likely obtain high S/N data on numerous radial velocity EGPs.
PECO can easily detect Jupiters

Trade study shows number of Jupiters detected for different telescope diameters

- PECO simulation Jupiter-like planets at 5 AU
- Assumes planet is detectable (SNR=5, R=5) in under 12 hr exposure (vertical line in figure) along 20% of its orbit. Single visit completeness > 20% in 12 hr exposure.
- hard IWA of 2 lambda/D - sources within 2 lambda/D are excluded. Including partially extinguished planets brings count from 88 to ~250 for 1.4m PECO.

Can see more targets at shorter wavelengths and larger diameters.
Disk imaging with PECO

- High sensitivity (<zodi) for large number of targets
- Full angular resolution (1 l/D): disk structures can be resolved by PECO
- Wide spectral coverage, from 400nm to 900nm & polarimetric imaging: dust properties

Figure 7-1: Face-on disk model provided by C. Stark (left) and simulated 1E4 x PECO 550nm image (right) of the Sun at 3.3 pc with a 1 zodi disk with the Earth (unseen) embedded at a distance of 3 AU.

Figure 7-2: Eps Eri ring simulation. The 3 AU radius ring was modeled by G. Schneider with a composition of rocky silicates, a width of 1 AU, inclined 22 degrees (same as its debris disk), and a total flux density of 1 zodi. Simulated for a central wavelength $\lambda = 550$ nm with a bandwidth $\delta \lambda = 110$ nm and an exposure time of $1E4$ seconds.
Simulated PECO imaging of Alpha Cent exozodi imaging

Model
1 zodi enhancement at 1AU

PECO image
3 hr exposure
400 nm, 20% band
# PECO Design Reference Mission

## Table: Mission Phases and Observation Times

<table>
<thead>
<tr>
<th>Mission Phase</th>
<th>Initial Detection and Characterization</th>
<th>Follow-up High SNR Characterization</th>
<th>Total (hours)</th>
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<tbody>
<tr>
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<td>Number of Systems</td>
<td>Integration (hours each)</td>
<td>Overhead (hours each)</td>
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<td>Commissioning</td>
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<td>-</td>
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<tr>
<td>Grand Tour Earths + Super-Earths</td>
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<td>16</td>
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<tr>
<td>Follow-up of Radial Velocity</td>
<td>15</td>
<td>16</td>
<td>8</td>
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<tr>
<td>Giant Planets + Disks Snapshot</td>
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<tr>
<td><strong>Total</strong></td>
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<td><strong>3-yr mission (hours)</strong></td>
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<tr>
<td><strong>Margin (hours)</strong></td>
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</table>

**Figure 8.3.2:** PECO-centric field of view for one moment in mission time. Sun/Earth avoidance and power-limited zones are outlined in blue. Continuous viewing zones are outlined in green. Grand Tour + RV targets are blue dots tagged with their HIP numbers. Please see the text in Sections 8.3.4 and 8.3.5 for detail.

Sun avoidance angle = 60 deg
anti-Sun avoidance angle = 45 deg
PECO top key technologies are identified and under study

- **PIAA Coronagraph System Path to TRL6**
  - PIAA mirror fabrication
  - Performance demonstrations in JPL HCIT
  - Brassboard component qualification
    - Note that existing PIAA coronagraph bench is the same scale as flight components
- **Broadband Wavefront Control**
  - Baseline Xinetics DM near TRL 6
  - MEMs DM technology in progress as potential cheaper alternative (NASA Ames Funding)
  - Algorithms tested in HCIT
- **Pointing Control Demonstration**
  - LOWFS provides fine guidance, to be tested in HCIT
  - Models predict 0.5 mas possible with existing technology (1 mas demonstrated with PIAA in the lab in air)
- **Photon-counting EMCCD Detectors**

**System verification combines:**
- **Subsystem testing & observatory testing**
- **Thermal-Structural-Optical modeling**
  - Needed for final system verification
  - HCIT will validate optical models
  - SIM TOM testbed demonstrated thermo-structural
PIAA optics – Diamond turning
Contrast achieved in 1.65 to 4.5 l/D half field zone (1 DM only):
2e-7 incoherent halo ghost (equivalent to exozodi)
4e-8 coherent starlight speckles (turbulence, vibrations)
Subaru PIAA lab demo

Contrast achieved (1.65 to 4 l/D):
Raw = 2.27e-7
Ghost = 1.63e-7
turbulence = 4.5e-8
coherent bias < 3.5e-9
2nd generation PIAA optics manufacturing completed by Tinsley on Jan 5 2009 (better surface accuracy, better achromatic design than PIAAgen1)
PIAA test status

PIAA gen2 is being tested in JPL’s High Contrast Imaging Testbed in vacuum and polychromatic light.

PIAA-dedicated testbed at NASA Ames testing WFC architectures & MEMs DMs (Belikov et al.).

Refractive PIAA system scheduled to be on-sky in early 2010 at Subaru Telescope.
• PECO optics don’t need to be very good, but they need to be STABLE

• Pointing stability requirements
  – Affects performance by:
    • Coronagraph leak from tip/tilt
    • Beam walk across optics creates speckles
  – Pointing jitter <1 milliarcseconds (mas) RMS
  – zero-point pointing drift should stay (or be known to) ~0.1 mas

• Dynamic and thermal disturbances
  – Affect low-order aberrations & mid spatial frequencies
  – Need to be stable to ~0.1 angstrom per mode during observation
  – Primary mirror stability is dominant source of error
  – Developed detailed error budget to derive rigid body motion requirements on optics and bending of PM
**Requirements:**
- 1 mas jitter (imposed by incoherent coronagraph leakage)
- Average centration stable to 0.1 mas within main wavefront control loop response time (several hrs)

**Acquisition**

**Reaction Wheels**
- Passive isolation (2 Hz low pass)
  - f~1 Hz

**Instrument**
- Actuated secondary mirror
- Fine steering mirror in instrument
  - f~10 Hz
  - f~100 Hz

**Spacecraft + OTA**
- Primary mirror
  - Requirement = 10 mas (imposed by beam walk effects)

**Coronagraph**
- LOWFS
LOWFS efficiently uses starlight to measure tip tilt and a few other low order modes. Subaru Testbed has demonstrated closed loop pointing control to $10^{-3}$ I/D ~ 0.1 mas on 1.4m PECO.

ref: Guyon, Matsuo, Angel 2009

Fig. 9.— CLOWFS focal plane mask used in the PIAA coronagraph laboratory testbed at Subaru Telescope. The 100 micron radius mask center is opaque (low reflectivity), and is surrounded by a 100 micron wide highly reflective annulus. The science field, transmitting light to the science camera, extends from 200 micron to 550 micron radius.

Fig. 10.— Laboratory performance for the CLOWFS. Upper left: Measured CLOWFS reference frame and influence functions for the 5 axis controlled in the experiment. Pre-PIAA and post-PIAA modes look extremely similar, as expected. Top right: Open loop simultaneous measurement of pre and post-PIAA modes. The measured amplitudes match very well the sine-wave signals sent to the actuators, and the CLOWFS is able to accurately measure all 4 modes shown here with little cross-talk. Since this measurement was performed in open loop, the measurement also include unknown drifts due to the limited stability of the testbed. Bottom left: Closed loop measurement of the residual error for the 5 modes controlled. The achieved pointing stability is about $10^{-3}$ $\lambda/D$ for both the pre-PIAA and post-PIAA tip/tilt. Bottom right: Position of the actuators during the same closed loop test.
PECO stability analysis

- PECO wavefront needs to be very stable
  - it takes few minutes to see an Earth-like planet
  - it takes just as long to see a speckle with the same luminosity
  - it takes a 1.5 pm sine wave ripple on the wavefront to create such a speckle
- A 1.5 pm sine wave ripple on the wavefront which appears in a few minutes is sufficient to confuse the detection of Earths
- Detailed analysis with design iterations have to be done to verify that PECO is sufficiently stable to detect Earths
PECO vibration analysis

- Identify vibration modes & frequencies
- Compute mode amplitude as a function of reaction wheel speed
- Use optical model to convert results in wavefront aberrations (tip/tilt, focus & other modes)

Analysis performed by Lockheed Martin
• PECO model shows jitter requirement can be met with no new technology
• Reaction wheels passively isolated
PECO thermal analysis

Thermal disturbance introduced when PECO sun angle is changed (pointing to new target)
How long after repointing does PECO become sufficiently stable?

• Compute displacements & rotations of PECO optics for a given thermal disturbance
• Estimate thermal disturbances evolution after PECO repointing
• Analysis ongoing. Preliminary results show PECO meets stability requirements after ~2hr

Analysis performed by Lockheed Martin. NASA JPL analysis effort also initiated.
PECO cost estimate

- PECO costed by JPL Team-X
- Independent Price-H model in good agreement with Team-X estimates

At this pre-phase A phase of the mission, cost estimate should be considered indicative rather than predictive

Total cost = $810M (with reserves)
$770M
+ $40M (technology development)

A 2-m version of PECO would increase cost to $1B to $1.5B range
4-year plan for technology development to TRL6, costed at $40M

<table>
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<th>Technology</th>
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<tr>
<td>Starlight Suppression</td>
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<tr>
<td>Pointing &amp; Dynamics</td>
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<td>EMCDD</td>
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**PECO technology development**

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<tr>
<th>TESTBED ACTIVITIES</th>
<th>NASA/ARC PIAA Exploratory Testbed</th>
<th>JPL HCIT CONFIGURATION</th>
<th>TECHNOLOGY MILESTONES</th>
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PECO can be launched in 2016
- **Telescope diameter**, currently 1.4m (cost constrained)
- **Drift-away** vs L2?
- **Active tip/tilt secondary** for pointing control?
- **Need for active isolation between payload & spacecraft vs passive isolation of reaction wheels only**?
- **Number of coronagraph channels & spectral coverage**
  - Currently 4 spectral channels in PECO design, 400nm to 900nm
  - More channels relaxes optical quality requirements at the expense of more complex instrument
- **Lower IWA PIAA coronagraph designs**
  - PIAA can be pushed theoretically to < I/D IWA at 1e10 contrast with Lyot stop and phase mask for point source
  - Sensitivity to pointing error, stellar leaks due to stellar diameter and chromaticity increase
  - Need to balance gains and losses taking into account all these effects
  - Strong potential to reduce IWA in the red PECO channels
- **MEMs as alternative to larger Xinetics Deformable mirrors**
  - Would allow smaller & cheaper instrument
  - Lab testing / validation (NASA Ames / JPL)
  - Number of actuators (32x32 to 64x64) defines PECO OWA
Summary

• PECO study shows **direct imaging and characterization of Earths/ Super-Earths possible with medium-scale mission** and:
  - maps exozodi down to <1 zodi sensitivity
  - census of planets and orbits in each exosystem
  - extrasolar giant planets characterization

• “Conventional” telescope with off-axis mirror can be used (stability OK, wavefront quality OK). All the “magic” is in the instrument -> **raising TRL for instrument is key (coronagraph, wavefront control)**
  - technology development at ~$40M, 4yr

• PECO could launch in 2016. Total mission cost ~$810M including technology development

• PECO architecture can be scaled to a flagship 3-4 m telescope without new technologies or new launch vehicles

• PECO team actively maturing technology, and exploring further improvements to coronagraph/WFC design
More info on PECO website: [http://caao.as.arizona.edu/PECO](http://caao.as.arizona.edu/PECO)
- 20-page summary of PECO activity
- Science Requirements Document (SRD)
- Design Reference Mission (DRM)
- Technology development plan
- Recent lab development updates

Several of the key coronagraphy and WFC technologies developed for PECO will be the core of the Subaru Coronagraphic Extreme-AO system
- PIAA & PIAACMC
- LOWFS for fast & accurate pointing control
- Control & calibration of focal plane speckles

Science goals: Planetary systems formation/architecture (young massive planets, disks), and possibly reflected light from massive planets