Terrestrial Planet Finder Coronagraph and Enabling Technologies

Virginia G. Ford
TPF-Coronagraph System Manager

REPRESENTING WORK OF TPF CORONAGRAPH TEAM
Searching for Extra-Solar Planets

- Since the mid 1980s dust disks around distant stars have been observed. Swirls and clear features in the observed disks indicate the presence of planets.
- New Neptune-mass planets reported, 31 August 2004.
  - GJ 436 b (Butler et al) 0.067 Mj
  - 55 Cnc e (McArthur et al) 0.045 Mj
  - HD 160691 d (Santos et al) 14 Me
- Spitzer observations of Exozodiacal dust (Astrophysical Journal, in press)
  - 266 nearby stars surveyed
  - 71 found to harbor disks
- Planets detected through August 2004
  - Blue dots show R-V detections
  - Red dots show transit detections
  - Yellow dot shows microlensing detection
Four Fundamental Facts About the Search for Planets and Life

1. Planets are a common outcome of star formation
   - Modern theory of star formation makes planet formation likely

2. The necessary ingredients of life are widespread
   - Observation reveals uniformity of physical and chemical laws
   - Origin of the elements and their dispersal is well understood
   - Carbon bond is unique and ubiquitous! Forget Silicon life.

3. Life affects a planet in a detectable way
   - Our own atmosphere reflects the presence of life

4. Life is Hardy
   - Extremophiles can live in hot (~120 C) acid lakes, near undersea volcanic vents, in underground aquifers, and within rocks in Antarctica
   - Life needs water, a source of energy, and cosmically abundant elements
Both wavelength bands needed to discern life-bearing atmospheres (prevent false positives).

Coronagraph to fly around 2014, Interferometer to fly around 2018.

Both wavelength bands needed to discern life-bearing atmospheres (prevent false positives).

Visible Coronagraphs (my system)

Formation Flying IR Interferometers

MISSION – TWO PARTS

• Search 30 to 150 nearby stars and detect planets in the habitable zone
  – Habitable zone (where liquid water can exist)
  – Defined for each star by its brightness

• Spectrally characterize the atmosphere to determine if any are terrestrial planets

MISSION – TWO PARTS

• Search 30 to 150 nearby stars and detect planets in the habitable zone
  – Habitable zone (where liquid water can exist)
  – Defined for each star by its brightness

• Spectrally characterize the atmosphere to determine if any are terrestrial planets

PROGRAM STRUCTURE

• Two teams developing two types of instruments

• Coronagraph to fly around 2014, Interferometer to fly around 2018
Theoretical Point Spread Function vs Radius

- Specially designed telescope required
  - Optimized to reduce diffraction speckle
- Wave Front Sensing and Control to correct wavefront errors

TPF Instrument PSF (c): Overlay: an exoplanetary system at 5 pc with Venus, Earth, Mars and Jupiters at 2.5, 5.0, 7.5, 10.0, and 12.5 AU respectively from left to right.
Two-fold Approach – Technology demonstration
  – Develop & analyze an architecture

Technology Demonstration

Current Activities
- Starlight suppression
- Wave Front Sensing and Control
- Masks and Stops development
- Large lightweight mirror development
- Coating design and analysis
- Picometer measurement of materials properties
- Modeling tool development that includes diffraction, polarization and precision that is required

Additional Activities
- Laser Metrology – leverage off of technology development from SIM and LISA
- Additional material properties measurements – leverage off of SIM testbeds
- Test and characterize structural microdynamic stability – leverage off of TPF-I studies
- Active Damping techniques – industry contribution

Architecture Development

• View 35 close stars
• Work at Inner Working Angle = 3\lambda/D
• Wavelength range: 500-800 nm
• First cut design based on Ball Aerospace Corp. study

- Deployed V-groove Thermal Shields (inner layer will act as baffle)
- Dynamic Isolation
- Spacecraft System
- Optical Bench: Coronagraph Sensor and Spectrograph
- Primary Mirror Support Structure (Aft Metering Structure)
- Science Payload - Telescope - Coronagraph System - Instruments
- Deployed Solar Array
- Thruster clusters (2)
- Fuel tanks (2)
- High gain antenna (2)
- Sun shade
Technology Development

Risk reduction advanced concepts:
Visible Nuller, Phase Mapping

Kodak Technology
Demonstration Mirror design and analysis

Mask Design and Analysis – TPF funded research at JPL, Berkeley, Ball Aerospace, GSFC and Princeton

Binary Mask Performance, Including Approximate Full-Wave effects

HEBS Glass Mask Design/Fabrication

High Contrast Imaging Testbed Remote Guest Testing in progress Contrast Results to date: $1.5 \times 10^{-9}$

University of Florida

High Contrast Enabling Technology
Xinetics, Inc. Deformable Mirrors in use in HCIT
Top: 64x64 actuator model
Bottom: 32x32 actuator model
Technology Development

- 70 nm waveband results – $5 \times 10^{-9}$
- Working on stability, polarization, broadening waveband
- New polarization monitoring equipment
- Binary to HEBS mask comparison measurements
Technology Development

Mask Design and Analysis – TPF funded research at JPL, Berkeley, Ball Aerospace, GSFC and Princeton

Binary Mask Performance, Including Approximate Full-Wave effects

To date in Testbed – HEBS glass masks are most successful but limited

HEBS Glass Mask Design/Fabrication

3. Linear $\sin^2$:

$$T(x) = T_{\text{max}} \left[ 1 - \alpha \left( \frac{\sin(\pi x / w)}{\pi x / w} \right)^2 \right]$$

$$T_{\text{max}} = 0.9, \alpha = 1 \text{ (no OD limit)}, w = 82.9 \mu m, x_{\text{max}} = 4 \times 82.9 = 331.6 \mu m$$

V. Ford  University of Florida
Starlight suppression systems have different characteristics that affect sensitivities.

New types of masks and systems are being designed and built to optimize for insensitivity to chromaticity, polarization, optical component motions.
Developing Technologies

Active Dynamics Damping
- Primary source of vibration during observation: Reaction Wheel Assembly (RWA)
- Used commercial RWA vibrations as inputs with Hubble passive damping parameters for models
- Active damping based on Lockheed Disturbance Free Payload system values

Laser Metrology System
- Optical metrology based on SIM and LISA Technology
  - Sub nanometer measurements
  - 6-DOF measurement Primary-Secondary positions
- Allocated tolerances: $\pm 1$ nm, $\pm 8$ nm x&y, $\pm 5$ nr x & y
- SIM Metrology can meet TPF-C requirements but laser frequency stability needs to be improved
- LISA laser stability meets TPF-C requirements, but may need different wavelength

Develop database of extremely precise materials properties
- Some measurement in work
- More needed
- Additionally will use data collected by other projects

V. Ford  University of Florida
Error Tree Terms

- **Mask Leakage**: image offset from ion-axis position allows light to diffract past the Lyot Stop.
- **Structural Deformation Beam Walk**: Tip/tilt/piston of optics causes transverse motion of the downstream beam across imperfect optics - modifies wave front and scatters light.
- **Structural Deformation Aberrations**: Perturbations cause wave front aberrations (even for perfect optics), scattering light to the image plane.
- **Deformation of Optics**: Bending of optics causes aberrations, scattering light.
- **Rigid Body Beam Walk**: Rigid body pointing errors of the optical train up to the fast-steering mirror result in transverse beam motion.
### Error Budget values

#### Deformation of Optics (Thermal)

<table>
<thead>
<tr>
<th>Zernike mode</th>
<th>Primary</th>
<th>Sec</th>
<th>Sf</th>
<th>Sp</th>
<th>Dm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>rms amp(Å)</td>
<td>rms amp(Å)</td>
<td>rms amp(Å)</td>
<td>rms amp(Å)</td>
<td>rms amp(Å)</td>
</tr>
<tr>
<td>4</td>
<td>0.022857</td>
<td>0.005714</td>
<td>0.002657</td>
<td>0.002857</td>
<td>0.002857</td>
</tr>
<tr>
<td>5</td>
<td>0.014286</td>
<td>0.003571</td>
<td>0.001786</td>
<td>0.001786</td>
<td>0.001786</td>
</tr>
<tr>
<td>6</td>
<td>0.014286</td>
<td>0.003571</td>
<td>0.001786</td>
<td>0.001786</td>
<td>0.001786</td>
</tr>
<tr>
<td>7</td>
<td>0.002857</td>
<td>0.000714</td>
<td>0.000357</td>
<td>0.000357</td>
<td>0.000357</td>
</tr>
<tr>
<td>8</td>
<td>0.002857</td>
<td>0.000714</td>
<td>0.000357</td>
<td>0.000357</td>
<td>0.000357</td>
</tr>
<tr>
<td>9</td>
<td>0.002857</td>
<td>0.000714</td>
<td>0.000357</td>
<td>0.000357</td>
<td>0.000357</td>
</tr>
<tr>
<td>10</td>
<td>0.002857</td>
<td>0.000714</td>
<td>0.000357</td>
<td>0.000357</td>
<td>0.000357</td>
</tr>
<tr>
<td>11</td>
<td>0.001429</td>
<td>0.000357</td>
<td>0.000179</td>
<td>0.000179</td>
<td>0.000179</td>
</tr>
<tr>
<td>12</td>
<td>0.002857</td>
<td>0.000714</td>
<td>0.000357</td>
<td>0.000357</td>
<td>0.000357</td>
</tr>
<tr>
<td>13</td>
<td>0.002857</td>
<td>0.000714</td>
<td>0.000357</td>
<td>0.000357</td>
<td>0.000357</td>
</tr>
<tr>
<td>14</td>
<td>0.002857</td>
<td>0.000714</td>
<td>0.000357</td>
<td>0.000357</td>
<td>0.000357</td>
</tr>
<tr>
<td>15</td>
<td>0.002857</td>
<td>0.000714</td>
<td>0.000357</td>
<td>0.000357</td>
<td>0.000357</td>
</tr>
</tbody>
</table>

#### Rigid body motions

<table>
<thead>
<tr>
<th>Element</th>
<th>Tilt (nR)</th>
<th>Tilt (mas)</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>4</td>
<td>0.8</td>
</tr>
<tr>
<td>y</td>
<td>4</td>
<td>0.8</td>
</tr>
<tr>
<td>z</td>
<td>4</td>
<td>0.8</td>
</tr>
</tbody>
</table>

#### Beam Walk Contrast due to pointing (rigid body)

<table>
<thead>
<tr>
<th>Element</th>
<th>Dx</th>
<th>2/D</th>
<th>3/D</th>
<th>4/D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>6.29E-07</td>
<td>6.14E-17</td>
<td>4.52E-17</td>
<td>8.01E-17</td>
</tr>
<tr>
<td>Secondary</td>
<td>8.40E-09</td>
<td>2.29E-17</td>
<td>2.27E-17</td>
<td>2.23E-17</td>
</tr>
<tr>
<td>Fold Mirror 1</td>
<td>6.78E-07</td>
<td>6.56E-14</td>
<td>6.84E-14</td>
<td>6.17E-14</td>
</tr>
<tr>
<td>Fold Mirror 2</td>
<td>9.05E-07</td>
<td>1.17E-13</td>
<td>1.22E-13</td>
<td>1.10E-13</td>
</tr>
<tr>
<td>DM Collimator</td>
<td>7.88E-07</td>
<td>2.90E-13</td>
<td>3.22E-13</td>
<td>2.63E-13</td>
</tr>
<tr>
<td>DM</td>
<td>1.72E-07</td>
<td>2.25E-33</td>
<td>1.65E-33</td>
<td>2.93E-33</td>
</tr>
<tr>
<td>Relay OAP2</td>
<td>1.97E-07</td>
<td>3.33E-23</td>
<td>3.69E-23</td>
<td>3.01E-23</td>
</tr>
<tr>
<td>BS1</td>
<td>1.50E-07</td>
<td>4.37E-16</td>
<td>4.56E-16</td>
<td>4.11E-16</td>
</tr>
<tr>
<td>BS1</td>
<td>1.43E-07</td>
<td>9.18E-15</td>
<td>9.57E-15</td>
<td>8.63E-15</td>
</tr>
<tr>
<td>BS1</td>
<td>1.61E-07</td>
<td>3.32E-16</td>
<td>3.47E-16</td>
<td>3.13E-16</td>
</tr>
<tr>
<td>BS2</td>
<td>1.21E-07</td>
<td>3.03E-16</td>
<td>3.16E-16</td>
<td>2.85E-16</td>
</tr>
<tr>
<td>BS2</td>
<td>1.09E-07</td>
<td>3.83E-16</td>
<td>3.99E-16</td>
<td>3.60E-16</td>
</tr>
<tr>
<td>BS2</td>
<td>5.27E-08</td>
<td>2.17E-16</td>
<td>2.26E-16</td>
<td>2.04E-16</td>
</tr>
<tr>
<td>Fold Mirror 3</td>
<td>4.89E-08</td>
<td>2.80E-15</td>
<td>2.92E-15</td>
<td>2.63E-15</td>
</tr>
<tr>
<td>Michelson BS</td>
<td>2.71E-08</td>
<td>4.09E-17</td>
<td>4.27E-17</td>
<td>3.85E-17</td>
</tr>
<tr>
<td>Michelson BS</td>
<td>2.04E-08</td>
<td>5.65E-16</td>
<td>5.89E-16</td>
<td>5.31E-16</td>
</tr>
<tr>
<td>Michelson BS</td>
<td>1.69E-08</td>
<td>1.09E-17</td>
<td>1.13E-17</td>
<td>1.02E-17</td>
</tr>
<tr>
<td>Wedge 1</td>
<td>3.87E-17</td>
<td>6.12E-18</td>
<td>6.38E-18</td>
<td>5.76E-18</td>
</tr>
<tr>
<td>Wedge 1</td>
<td>2.33E-13</td>
<td>4.21E-18</td>
<td>4.39E-18</td>
<td>3.96E-18</td>
</tr>
<tr>
<td>Wedge 1</td>
<td>2.81E-13</td>
<td>7.98E-28</td>
<td>8.32E-28</td>
<td>7.51E-28</td>
</tr>
<tr>
<td>Wedge 1</td>
<td>3.74E-13</td>
<td>1.16E-27</td>
<td>1.21E-27</td>
<td>1.09E-27</td>
</tr>
<tr>
<td>Michelson BS</td>
<td>6.90E-13</td>
<td>2.66E-27</td>
<td>2.15E-27</td>
<td>1.94E-27</td>
</tr>
<tr>
<td>Michelson BS</td>
<td>7.26E-13</td>
<td>7.02E-27</td>
<td>7.32E-27</td>
<td>6.60E-27</td>
</tr>
<tr>
<td>Michelson BS</td>
<td>1.80E-12</td>
<td>7.76E-27</td>
<td>8.09E-27</td>
<td>7.30E-27</td>
</tr>
<tr>
<td>Fold Mirror 4</td>
<td>7.87E-12</td>
<td>7.67E-25</td>
<td>7.99E-25</td>
<td>7.21E-25</td>
</tr>
<tr>
<td>Relay OAP3</td>
<td>6.15E-12</td>
<td>2.04E-23</td>
<td>2.26E-23</td>
<td>1.84E-23</td>
</tr>
<tr>
<td>Relay OAP4</td>
<td>6.71E-12</td>
<td>2.43E-23</td>
<td>2.69E-23</td>
<td>2.20E-23</td>
</tr>
<tr>
<td>Reflector Flat</td>
<td>2.10E-11</td>
<td>1.04E-22</td>
<td>1.08E-22</td>
<td>9.74E-23</td>
</tr>
<tr>
<td>Occulting Mask R</td>
<td>2.81E-11</td>
<td>1.87E-22</td>
<td>1.95E-22</td>
<td>1.76E-22</td>
</tr>
<tr>
<td>Exit Pupil Return</td>
<td>1.91E-13</td>
<td>8.59E-27</td>
<td>8.96E-27</td>
<td>8.08E-27</td>
</tr>
</tbody>
</table>

---

Motions utilized for jitter and aberration sensitivity
This is for all elements except Primary and Secondary

<table>
<thead>
<tr>
<th>Element</th>
<th>Tilt (nR)</th>
<th>Translation (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fold1</td>
<td>5.00</td>
<td>5.00</td>
</tr>
<tr>
<td>Fold2</td>
<td>5.00</td>
<td>5.00</td>
</tr>
<tr>
<td>DM OAP1</td>
<td>5.00</td>
<td>5.00</td>
</tr>
<tr>
<td>Pol-BS1</td>
<td>5.00</td>
<td>5.00</td>
</tr>
<tr>
<td>Pol-BS2</td>
<td>5.00</td>
<td>5.00</td>
</tr>
<tr>
<td>Fold3</td>
<td>5.00</td>
<td>5.00</td>
</tr>
<tr>
<td>Michelson BS</td>
<td>5.00</td>
<td>5.00</td>
</tr>
<tr>
<td>Wedge 1</td>
<td>5.00</td>
<td>5.00</td>
</tr>
<tr>
<td>DM</td>
<td>5.00</td>
<td>5.00</td>
</tr>
<tr>
<td>Fold4</td>
<td>5.00</td>
<td>5.00</td>
</tr>
<tr>
<td>Relay OAP2</td>
<td>5.00</td>
<td>5.00</td>
</tr>
<tr>
<td>Relay OAP3</td>
<td>5.00</td>
<td>5.00</td>
</tr>
<tr>
<td>Reflector (OAP4)</td>
<td>5.00</td>
<td>5.00</td>
</tr>
<tr>
<td>Reflector Flat</td>
<td>5.00</td>
<td>5.00</td>
</tr>
<tr>
<td>Occulting Mask Return</td>
<td>5.00</td>
<td>5.00</td>
</tr>
<tr>
<td>Exit Pupil Return</td>
<td>5.00</td>
<td>5.00</td>
</tr>
</tbody>
</table>
Analysis of Minimum Mission Concept

- Completed modeling and analysis in June
- Mission operations concept:
  1. Acquire target star
  2. Settle, observe and set Deformable Mirror, read out focal plane
  3. Dither (rotate 20 degrees around line-of-sight)
  4. Observe and read out focal plane
  5. Compare observations – subtract to eliminate speckles
  6. Rotate 70 degrees around line-of-sight
  7. Repeat steps 2 – 5 to obtain other axis resolution
- Primary mirror 6 m x 3.5 m with 10 m spacing to secondary mirror
- Since then have been working toward developing flight baseline design
Minimum Mission Concept Assemblies

- Deployed secondary tower
- Cross section of deployed V-groove layers
- V-groove deployment boom
- Spacecraft equipment support panel
- Primary mirror thermal enclosure (coronagraph sensor and spectrograph inside)
- Deployed solar array
- Deployed v-groove platform
- Propulsion tank (2 pi)
- Spacecraft equipment support panel
- Thruster cluster (2 pi)
- Spacecraft bus
- Reaction wheels (6)
- Dynamic isolation (3 pi)
- Spacecraft equipment support panel
- S/C thermal isolators
- Frame
- Cross section of deployed V-groove layers

Not shown: Laser Metrology “truss”

- Secondary Bracket
- Thermal Enclosure
- Acquisition Camera
- Primary mirror (6m x 3.5m)

University of Florida

V. Ford
## Minimum Mission Thermal Modeling

**Telescope Steady-State Temperature for Two 20 deg Dither Cases (80 to 100 & 170 to 190)**

<table>
<thead>
<tr>
<th>Temperature (C) Distribution for all Sun Angles</th>
<th>Delta Temperature (C) for Dither from 80 to 100</th>
<th>Delta Temperature (C) for Dither from 170 to 190</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steady State, Sun at 180 deg</td>
<td>Dither from 80 to 100 deg</td>
<td>Dither from 170 to 190 deg</td>
</tr>
<tr>
<td>Front Face Sheet of PM 0.69 mK p-v</td>
<td>Front Face Sheet of PM 0.14 mK p-v</td>
<td>Front Face Sheet of PM 0.14 mK p-v</td>
</tr>
</tbody>
</table>

V. Ford  
University of Florida
**Thermal Modeling Results**

**Summary for PM Design with Optimized Segment Placement**
Based on 80 to 100 deg Dither

<table>
<thead>
<tr>
<th>Zemike Comp</th>
<th>Stead-State Resp (pm)</th>
<th>3L/D Req Specs (pm)</th>
<th>Ratio</th>
<th>Req/Resp</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.14</td>
<td>2.29</td>
<td>16.21</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.19</td>
<td>0.29</td>
<td>1.47</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>0.09</td>
<td>0.14</td>
<td>1.64</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>0.11</td>
<td>0.29</td>
<td>2.53</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>0.07</td>
<td>0.29</td>
<td>3.86</td>
<td></td>
</tr>
</tbody>
</table>

**Results for 170 to 190 deg Dither**
Using Optimized Segment Placement

<table>
<thead>
<tr>
<th>Zemike Comp</th>
<th>Stead-State Resp (pm)</th>
<th>3L/D Req Specs (pm)</th>
<th>Ratio</th>
<th>Req/Resp</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.02</td>
<td>2.29</td>
<td>126.52</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.06</td>
<td>0.29</td>
<td>4.88</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>0.01</td>
<td>0.14</td>
<td>22.70</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>0.01</td>
<td>0.29</td>
<td>40.28</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>0.03</td>
<td>0.29</td>
<td>9.93</td>
<td></td>
</tr>
</tbody>
</table>

Note: The results for PM with optimal segment placement are steady-state (conservative for dither)

V. Ford University of Florida
Dynamic Vibration Input:

Reaction Wheel Assemblies with two layers of passive vibration isolation

Materials Used:

- ULE Glass (Ultra-Low Expansion Titanium Silicate Glass by Corning)
  - Primary & Secondary Mirrors (good thermal stability)

- K1100/954 Carbon Fiber Composite
  - Primary & Secondary Mirror Thermal Enclosures (high conductivity)

- S-Glass Fiberglass Composite
  - AMS/secondary tower bracket & SMA isolators, launch struts (low conductivity)

- M55J/954 GrEp
  - AMS, secondary tower & bracket (good thermal stability & stiffness)

Dynamic Results - 2 stage passive isolation

Flexible Primary Wavefront Error

Mode 8 exceedance can be avoided by running wheels above 4hz

Rigid Optics Wavefront Error

Design meets requirements passively

---

Flexible Primary Wavefront Error

Mode 8 exceedance can be avoided by running wheels above 4hz
Flight Baseline Architecture – in work

- Many open trades
- Work in progress
A typical AstroMesh rim truss supports an array of radial cables.

Shrouds are attached to lower radial cables

Shroud extensions between radials shield rim truss

Four Telescopic Booms support the deployed rim truss

V. Ford University of Florida
Summary

Starlight suppression research is advancing rapidly to approach the required contrast ratio.

The current analysis of the TPF Coronagraph system indicates that it is feasible to achieve the stability required by using developing technologies:

- Wave Front Sensing and Control (DMs, control algorithms, and sensing)
- Laser metrology

Yet needed:

- Property data measured with great precision in the required environments
- Modeling tools that are verified with testbeds