Technology and Design of an Infrared Interferometer for the Terrestrial Planet Finder

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Acknowledgements

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The Search for Habitable Planets

Mission Concept Downselect -- Choose between:

Visible / NIR Coronagraph

Mid-IR Interferometers
Fundamentals Regarding the Search for Planets and Life

- The necessary ingredients of life are widespread

- Life on Earth can inhabit harsh environments

- Life affects a planetary environment in a detectable way

- Planets are a common outcome of star formation
Gas Giant Planets

- Over 100 planets found using radial velocity wobble
  - ~10% of stars have planets
  - Most orbits < 2-3 AU
  - Half may be multiple systems

- Planets on longer periods starting to be identified
  - 55 Cancri is solar system analog
- Astrometry (SIM) and radial velocity will determine solar system architecture to few $M_\oplus$

<table>
<thead>
<tr>
<th>Planet</th>
<th>Mass (M_J)</th>
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<tbody>
<tr>
<td>HD187123</td>
<td>0.57</td>
</tr>
<tr>
<td>HD75289</td>
<td>0.42</td>
</tr>
<tr>
<td>Tau Boo</td>
<td>3.60</td>
</tr>
<tr>
<td>51 Peg</td>
<td>0.14</td>
</tr>
<tr>
<td>Ups And</td>
<td>0.73</td>
</tr>
<tr>
<td>HD217107</td>
<td>1.20</td>
</tr>
<tr>
<td>HD130322</td>
<td>1.00</td>
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<tr>
<td>55CnC</td>
<td>0.85</td>
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<tr>
<td>GL86</td>
<td>0.90</td>
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<tr>
<td>HD195019</td>
<td>3.40</td>
</tr>
<tr>
<td>GL876</td>
<td>2.10</td>
</tr>
<tr>
<td>Rho Crb</td>
<td>1.10</td>
</tr>
<tr>
<td>HD168443</td>
<td>5.00</td>
</tr>
<tr>
<td>HD114762</td>
<td>11.0</td>
</tr>
<tr>
<td>70 Vir</td>
<td>7.40</td>
</tr>
<tr>
<td>Iota Hor</td>
<td>2.20</td>
</tr>
<tr>
<td>HD10277</td>
<td>1.30</td>
</tr>
<tr>
<td>16 Cyg B</td>
<td>1.60</td>
</tr>
<tr>
<td>47UMa</td>
<td>2.30</td>
</tr>
<tr>
<td>14 Her</td>
<td>3.30</td>
</tr>
</tbody>
</table>

Jupiter

Earth

Our Solar System

55 Cancri System

Marcy et al.
TPF Science (1)

- Detect and characterize terrestrial-sized planets around nearby stars
- Complete survey within 2 yrs:
  - Late F, G, K dwarf stars
    - Full Survey on >30 stars
    - Partial Survey on >120 stars
  - Full survey on >150 stars
- Survey Detection Parameters:
  - Completeness 95%
  - Continuously Habitable Zone:
    - 0.7 to 1.5 AU (G-dwarf) – Earth albedo, One Earth surface area
    - 0.9 to 1.1 AU (G-type) – Earth albedo, half Earth surface area
      - At least 3 visits
- Large Field of View (0.5 to 1 arcsec) to characterize Jovian planets in subset of stars
TPF Science (2)

- Obtain Spectra: determine the presence of an atmosphere
- Detect:
  - Water
  - Carbon Dioxide
  - Oxygen 10zone
  - Methane
- Wavelength:
  6.5 - 13μm (17 desirable), SR=25
  0.5 - 0.8μm (1.05 desirable), SR= 75
- Spectral resolution of R>100 for brightest sources
- Desire detection of Rayleigh scattering, absorption edges of photosynthetic pigments.

Planetary Spectral Signature

Intensity vs Wavelength, μm
Four Hard Things About TPF

- **Sensitivity (relatively easy)**
  - Detection in hours, days → spectroscopy in days, weeks.
  - Integration time $\propto (\text{distance/diameter})^4$
  - Need 12 m$^2$ of collecting area ($\geq 4$ m) for star at $\sim 10$ pc

- **Angular resolution (hard)**
  - 100 mas is enough to see $\sim 25$ stars, but requires $\geq 4$ m coronagraph or $\geq 20$ m interferometer
  - Baseline or (aperture) $\propto$ distance

- **Starlight suppression (hard to very hard)**
  - $10^{-6}$ in the mid-IR
  - $10^{-10}$ in the visible/near-IR

- **Solar neighborhood is sparsely populated**
  - Fraction of stars with Earths (in habitable zone) unknown
  - Unknown how far we need to look to ensure success
  - Surveying substantial number of stars means looking to $\sim 15$ pc
Instrument Approaches

- Shift phase of one input beam by $\pi$ rad
- Rotate Array
- Chop the pairs
TPF Coronagraph straw man (minimum mission)

- Deployed Secondary w/tower, laser metrology and 6 DOF actuators
- Deployed Telescope Baffle/Inner Thermal Shield
- Deployed V-groove Thermal Shields (4 plus telescope baffle) - 3 degree separation between layers
- Primary mirror: 6m x 3.5m (3.5 m dimension shown) - active surface correction possible
- Active thermal control for 20C operation

Instruments:
- Coronagraph Sensor and Spectrograph
- Wavefront Sensing and Control
- Masks and Stops and alternatives

Active Dynamic Isolation
Thermal Isolation
Communication Antenna
Instrument Electronics
Bus
Spacecraft
Deployed Solar Array (10 m²)
TPF Coronagraph Conceptual Design

V-groove thermal shields

Sequence for stowing in launch shroud – Delta IV Heavy

Secondary

Primary mirror
Interferometer Systems

Will Deliver

corpus for the

*full* TPF science

corpus for the

*minimum* TPF science

, end-to-

end , and

to demonstrate

viability of concepts
Architecture Trades

- Considered many different nulling architectures
- Narrowed trade space to those below by considering
  - Exo zodi suppression
  - Instrument background suppression
  - Feasible beam combiner
Architecture Trades

- Figures of Merit
  - Total number of stars surveyed
  - Number of nearby stars (<5 parsec)
- Considered
  - Resolution vs null width (stellar suppression)
  - Sensitivity (limited integration time)
  - Feasible aperture sizes, limited by fairing
    - ~3.5m for
    - ~3.0 to 3.5 for
  - Feasible structure sizes, limited by fairing
    ~40-50m
Structurally – Connected Baseline Configuration

- Dual Chopped Bracewell – greatest resolution for given array size
- Array Length: 36m
- 3.2m diameter apertures (Quantity 4)
- ± 45 degrees sky coverage (from anti-sun)
- ~ 50 stars surveyed

SCI – limited by resolution
Collaboration on TPF/Darwin
## FFI Configuration Trades

<table>
<thead>
<tr>
<th>Design Feature</th>
<th>Minimum Science Mission</th>
<th>Full Science Mission</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>(A)</td>
<td>(B)</td>
</tr>
<tr>
<td><strong>Platform</strong></td>
<td>Connected Structure</td>
<td>Formation Flying</td>
</tr>
<tr>
<td><strong>Input pupil</strong></td>
<td>Dual Bracewell</td>
<td>Dual Bracewell</td>
</tr>
<tr>
<td><strong>Array size</strong></td>
<td>36m</td>
<td>70m</td>
</tr>
<tr>
<td><strong>Collecting Area</strong></td>
<td>4 x 3.2m diameter apertures</td>
<td>4 x 3.0m diameters apertures</td>
</tr>
<tr>
<td><strong>No. of Launches</strong></td>
<td>1</td>
<td>1</td>
</tr>
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</table>

*limited by sensitivity.*
IR Interferometer: Top Technical Concerns

- Concerns Prioritized by
  - Gap (Seriousness)
  - Urgency
  - Trend

  Mitigated by
  - Inheritance
  - System Engineering
  - Technology Development
# Top Concerns: Core Interferometry

<table>
<thead>
<tr>
<th>Category</th>
<th>Primary Concern</th>
<th>TPF Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starlight Nulling Beamtrain</td>
<td>Nulling architecture</td>
<td>Survey 30-150 stars for terrestrial planets</td>
</tr>
<tr>
<td></td>
<td>Beam combination</td>
<td>4 or 6 beams, $10^{-5}$ null 6.5-17$\mu$m</td>
</tr>
<tr>
<td></td>
<td>Internal thermal emissions</td>
<td>$&lt;&lt;100$ photons/sec</td>
</tr>
<tr>
<td></td>
<td>Spatial Filters</td>
<td>70% throughput in single mode, 6.5-17$\mu$m</td>
</tr>
<tr>
<td></td>
<td>Intensity matching</td>
<td>0.2%</td>
</tr>
<tr>
<td></td>
<td>Phase control</td>
<td>1nm (all frequencies)</td>
</tr>
<tr>
<td>Instrument Controls</td>
<td>Pointing control accuracy of compressed beam</td>
<td>50 mas</td>
</tr>
<tr>
<td></td>
<td>Cryogenic delay line closed loop stability</td>
<td>0.1 nm at 40K</td>
</tr>
<tr>
<td>Detectors</td>
<td>Cryocoolers</td>
<td>30mW at 6K</td>
</tr>
<tr>
<td>Category</td>
<td>Primary Concerns</td>
<td>TPF Requirements</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>------------------------------------------</td>
<td>-----------------------------------------------------------------------</td>
</tr>
<tr>
<td>Formation-Flying System</td>
<td>Long-term system robustness</td>
<td>5-10 years</td>
</tr>
<tr>
<td></td>
<td>Performance of fine formation control</td>
<td>1 cm range, 20 arcsec bearing accuracy</td>
</tr>
<tr>
<td></td>
<td>Algorithm functionality</td>
<td>5 s/c autonomous sensing collision avoidance performance</td>
</tr>
<tr>
<td></td>
<td>In deep space</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Course acquisition sensor</td>
<td>50 cm, 1 deg, $4\pi$ steradian FOV with no calibration maneuvers</td>
</tr>
<tr>
<td>Formation Flying Accommodation</td>
<td>RF interference from thermal shield</td>
<td>Low multipath effects on RF range measurements</td>
</tr>
<tr>
<td></td>
<td>Inters s/c stray light</td>
<td>$&lt;&lt;100$ photons/sec</td>
</tr>
</tbody>
</table>
## Top Concerns: Connected Structure

<table>
<thead>
<tr>
<th>Category</th>
<th>Primary Concern</th>
<th>TPF Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precision</td>
<td>Stability of long Cryogenic structure</td>
<td>1nm/36m40K</td>
</tr>
<tr>
<td>Cryogenic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deployed Structure</td>
<td>Cryo hinge and latch stability</td>
<td>&lt; 100m</td>
</tr>
<tr>
<td></td>
<td>Structural modeling tools</td>
<td>Confident prediction of performance</td>
</tr>
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</table>

![Diagram of connected structure](image)
## Other Top Concerns

<table>
<thead>
<tr>
<th>Category</th>
<th>Primary Concern</th>
<th>TPF Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flight &amp; Mission System</strong></td>
<td>Launch packaging of structure, formation flight systems</td>
<td>Self imposed</td>
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<tr>
<td></td>
<td>Interspacecraft communications</td>
<td>Continuous reliable high data rate 4 Mbits/sec</td>
</tr>
<tr>
<td></td>
<td>Sky coverage</td>
<td>At least +/- 45 deg</td>
</tr>
<tr>
<td><strong>Integration and Performance Verification</strong></td>
<td>End to end flight system test</td>
<td>Ability to verify multi-collector distributed flight system</td>
</tr>
<tr>
<td></td>
<td>Overall system complexity</td>
<td>Acceptable risk</td>
</tr>
</tbody>
</table>
System Engineering

• Orbit: L2
• Launch Vehicle: Delta IV Heavy
• Fairing: 22.4m
• Power: Solar Arrays
• Coarse formation sensor: RF
• Open Trades: SCI configuration: 6 fold oblique
  – Sunshield configuration and deployment
  – Telescope optical design
  – Fine pointing control technology
  – Timing of formation or boom deployment
Launch Vehicle packaging
Achromatic Nulling Testbed

- Stable $10^{-6}$ white light null with 50% bandwidth
- 7-12 $\mu$m
Planet Detection Testbed

- 4-beam demonstration of dual-chopped Bracewell
  - Planet extraction ($10^{-6}$ planet/star contrast), laser
  - $10^{-6}$ null depth
  - $10^{-7}$ null stability
  - Amplitude and phase control
Core Interferometer Technology

Mid-Infrared Spatial Filters

Cryogenic Delay Line

Adaptive Nuller

Deformable Mirror
Cryogenic Structures Technology

Structurally-Connected Interferometer Testbed

Cryogenic Structures Technology
Formation Flying Technology

FAST

Formation Control Testbed

Formation Sensor Testbed

MIT Spheres
Overriding goal: Find one design that is scientifically compelling and technologically ready for 2008 NAS Decadal Review and 2015 launch