Architecture Trade Study for the Terrestrial Planet Finder Interferometer

*JPL*

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Introduction

- A systematic, quantitative comparison of leading architectures

- Architecture = # collectors & combiners, geometric nulling config, aperture size, # launches

- 6 basic options, judged against ~45 metrics

- Select best architecture for detailed interim study by Design Team

- Completed in December 2004

- Not the final architecture for TPF-I!
Nulling configurations

- Linear DCB
- X-Array
- Diamond DCB
- Z-Array
- Triangle
- Linear 3

Not considered:
- \( \theta^4 \) nulls
- Single Bracewell
- Structurally-connected

Common themes
- All \( \theta^2 \) null
- All \( \leq 5 \) spacecraft
- Dual Chopped Bracewell family
Constraints: delay equalization

X-Array

Linear DCB

Linear 3

Triangle

Diamond DCB

Z-Array
Constraints: aperture size

- Constrained by launch vehicle
  - Boeing Delta IV Heavy
  - 9600 kg launch mass
  - 4.6 m fairing diameter
  - 17 m fairing height
  - 30% mass margin
- Assumed circular monolithic mirrors
- Created parametric models of mass, height and diameter of launch package vs primary mirror diameter and # spacecraft

<table>
<thead>
<tr>
<th>Config</th>
<th># spacecraft</th>
<th>D / m</th>
<th>Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td># comb</td>
<td># coll</td>
<td></td>
</tr>
<tr>
<td>Linear DCB</td>
<td>1</td>
<td>4</td>
<td>3.8</td>
</tr>
<tr>
<td>X-Array</td>
<td>1</td>
<td>4</td>
<td>3.8</td>
</tr>
<tr>
<td>Diamond DCB</td>
<td>0</td>
<td>4</td>
<td>4.1</td>
</tr>
<tr>
<td>Z-Array</td>
<td>0</td>
<td>4</td>
<td>4.1</td>
</tr>
<tr>
<td>Linear 3</td>
<td>1</td>
<td>3</td>
<td>4.1</td>
</tr>
<tr>
<td>Triangle</td>
<td>0</td>
<td>3</td>
<td>4.1</td>
</tr>
</tbody>
</table>
Constraints: array size

Minimum
- Safe separation for formation flying
- Minimum tip-to-tip spacing = 5 m
- Minimum center-to-center = 20 m
- **Impact:** increases integration time for nearby stars

Maximum
- Stray light from sunshades
- Maximum center-to-center = 80 m
- **Impact:** limits inner working angle and angular resolution
Process

- 8 mandatory criteria (*musts*)
- 26 additional discriminators covering performance and cost/risk (*wants*)
  - Weights were assigned to each *want*
    - subjective
    - average of all inputs obtained
    - normalized to give a sum of 100
    - 43% performance; 57% cost/risk
- Each option was scored out of 10 against each of the criteria
  - based on quantitative metrics in most cases
- Each score is multiplied by the weight and summed over all criteria to give total score out of 1000
Performance: observable stars (21.5%)

- Total stars surveyed (4.9%)
- Stars < 5 pc surveyed (3.4%)
- Overlap with TPF-C stars (5.6%)
- Spectroscopic characterizations (7.6%)

Distance / pc

IHZ semi-major axis / mas

$T_{\text{int}} \sim 1 \text{ day}$

Linear DCB 229
Z-Array 109

Local Zodi dominates (configuration, aperture)

Inner Working Angle (stray light, configuration)

Stellar leakage dominates (configuration)
Performance: imaging (5.7%)

- Important for separating contributions from multiple planets and lumps in the EZ

- Metrics
  - Angular resolution: FWHM of synthesized point spread function
  - Sidelobes: rms of sidelobes relative to main peak
  - Degeneracy: # peaks (e.g. triangle configuration has 3 symmetric peaks)

- Supported by simulations of planet signal extraction
Performance: other issues

- **General astrophysics capability (4.4%)**
  - Dynamic range of baselines (imaging)
  - Max angular resolution
  - # distinct simultaneous baselines (imaging)
  - Ease of implementing a co-phasing beam train (faint targets)

- **Calibration time needed (4.4%)**
  - Increases with number of collectors

- **Redundancy / graceful degradation (4.3%)**
  - Performance after loss of a collector
  - Expected mission productivity, given failure probabilities for each spacecraft

- **Ability to suppress non-symmetric star features (3.3%)**
  - Calculated sensitivity to star spots
Cost (57%)

- There was no attempt to estimate $ costs for the options directly
- The following items were identified as proxies for cost:

  - # launches (8.7%)
    - Considered dual-launch options for Linear DCB and X-Array
    - Adds cost and operations complexity (rendezvous)

  - Control system complexity (4.8%)
    - # control loops (ranged from 18 to 26)

  - # different types of spacecraft (4.7%)
    - Non-recurring costs are expected to be major driver

  - Difficulty of I&T (4.4%)
    - # spacecraft
    - # spacecraft needed for end-to-end beamtrain
    - Collector aperture diameter (impacts size of pseudostar needed)
    - Minimum array length (ability to fit into vacuum tank)
Cost II

- **Beam transport complexity (4.1%)**
  - # hops from collector to combiner

- **Beam combiner complexity (4.1%)**
  - # parts needed
  - Requires achromatic phase shifts other than 0 or 180 deg?

- **# mechanisms / moving parts (3.7%)**
  - e.g. deployable secondary, sunshade, HGA, cryo-cooler
Cost III

- Equal size primary mirrors (2.7%)
- # spacecraft (2.6%)
- Mass margin (2.6%)
- Difficulty of thermal control (2.6%)
- Complexity of flight operations (2.6%)
- Concept maturity (2.3%)
- Adaptability to different prevalence of earth-like planets (2.2%)
- Fuel usage (1.7%)
- Legacy (technology useful to future missions) (1.6%)
- Complexity of inter-S/C comm. & coarse formation sensing (1.2%)
## Results

<table>
<thead>
<tr>
<th>System</th>
<th>Score /1000</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-Array</td>
<td>841</td>
<td>- 2 types of spacecraft (+14)</td>
<td>- # Stars surveyed (-9)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Simple beam relay (+12)</td>
<td>- General Astrophysics (-7)</td>
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<tr>
<td></td>
<td></td>
<td>- Degrades gracefully (+6)</td>
<td></td>
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<tr>
<td>Linear DCB</td>
<td>805</td>
<td>- # stars surveyed</td>
<td>- # spacecraft</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Spectroscopy performance</td>
<td>- Mass margin</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>- Ease of I&amp;T</td>
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<tr>
<td>Diamond DCB</td>
<td>774</td>
<td>- Ease of I&amp;T (+8)</td>
<td>- Graceful degradation (-17)</td>
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<tr>
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<td></td>
<td>- # mechanisms (+4)</td>
<td>- Spectroscopy performance (-16)</td>
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<tr>
<td></td>
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<td>- # spacecraft (+4)</td>
<td>- General Astrophysics (-7)</td>
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<tr>
<td>Linear 3*</td>
<td>772</td>
<td>- Ease of I&amp;T (+8)</td>
<td>- Spectroscopy performance (-30)</td>
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<tr>
<td></td>
<td></td>
<td>- Calibration time (+7)</td>
<td>- Redundancy (-15)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Mass margin (+6)</td>
<td>- Beam combiner complexity (-14)</td>
</tr>
<tr>
<td>Triangle*</td>
<td>731</td>
<td>- Ease of I&amp;T (+20)</td>
<td>- # Stars surveyed (-42)</td>
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<td>- Mass margin (+15)</td>
<td>- Spectroscopy performance (-35)</td>
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<td>- Flight operations (+12)</td>
<td>- General Astrophysics (-17)</td>
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<td>- Ease of I&amp;T (+6)</td>
<td>- # Stars surveyed (-43)</td>
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<tr>
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<td>- # mechanisms (+4)</td>
<td>- Spectroscopy performance (-25)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- # spacecraft (+4)</td>
<td>- General Astrophysics (-17)</td>
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</table>
Update to SPIE paper
Max array size update

- For trade study, max. separation = 80 m
- Following an optimization of the beam transport, max. separation = 165 m
- Leads to doubling of max. array size for each configuration
Impact on star counts

- Little change to Linear DCB
  - Not limited by IWA during survey
- 50% increase for Z-Array
  - Previously most constrained by stray light

- Spectroscopy uses larger array sizes than survey to get sufficient angular resolution
- Factor 3 increase for Triangle and Linear 3
## Impact on trade study scores

<table>
<thead>
<tr>
<th>New</th>
<th>Linear DCB</th>
<th>X-Array (2:1)</th>
<th>Diamond DCB</th>
<th>Z-Array</th>
<th>Triangle</th>
<th>Linear 3</th>
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<tbody>
<tr>
<td>Overall score / 1000</td>
<td>816</td>
<td>860</td>
<td>789</td>
<td>749</td>
<td>779</td>
<td>795</td>
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<tr>
<td>Performance</td>
<td>381</td>
<td>385</td>
<td>337</td>
<td>341</td>
<td>292</td>
<td>342</td>
</tr>
<tr>
<td>Cost / risk</td>
<td>435</td>
<td>475</td>
<td>452</td>
<td>408</td>
<td>487</td>
<td>452</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Old</th>
<th>Linear DCB</th>
<th>X-Array (2:1)</th>
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<tr>
<td>Overall score / 1000</td>
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<td>841</td>
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<td>731</td>
<td>Failed</td>
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<tr>
<td></td>
<td></td>
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<td>772</td>
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<tr>
<td>Performance</td>
<td>370</td>
<td>365</td>
<td>323</td>
<td>280</td>
<td>244</td>
<td>319</td>
</tr>
<tr>
<td>Cost / risk</td>
<td>435</td>
<td>475</td>
<td>452</td>
<td>408</td>
<td>487</td>
<td>452</td>
</tr>
</tbody>
</table>

- X-Array extends margin over Linear DCB
- Triangle and Linear 3 pass now pass mandatory criterion
- All options score higher
- Largest boost for Z-Array and Triangle
Conclusions

- X-Array identified as the leading option
- Dual-launch options ranked lower than single launch
- The decision process is subjective but transparent
- Intended to reflect our engineering judgment, not dictate it
- This is not the final architecture for TPF-I
- A quantitative framework for assessing new architectures and optimizing the existing ones
- See paper for full breakdown
Back-up
Constraints: proximity

- **Linear DCB**
  - Min Array size: 60 m

- **X-Array**
  - Min Array size: 40 m

- **Diamond DCB**
  - Min Array size: 35 m

- **Z-Array**
  - Min Array size: 66 m

- **Triangle**
  - Min Array size: 20 m

- **Linear 3**
  - Min Array size: 40 m

- Minimum spacecraft separation = 20 m (center-to-center)
- ~ 5 m shade-to-shade

**Increased integration time for nearby stars**
Constraints: stray light

Max Array size

- Linear DCB: 240 m
- X-Array: 160 m
- Diamond DCB: 140 m
- Z-Array: 88 m\(^*\) \(L_{\text{max}} < L_{\text{min}} (66 \text{ m})\)
- Triangle: 80 m
- Linear 3: 160 m

Maximum spacecraft separation = 80 m (center-to-center)

Limits Inner Working Angle
Inner Working Angle

- Example: Linear 3 configuration

  - “Put the planet on the first fringe”

- More sophisticated version from modulation efficiency curve:

  - IWA = 27 mas @ 10 um => L = 46 m
Linear 3, dirty map

- Linear 3, 46 m baseline
- Venus – Earth – Mars orbits, equal flux
- IHZ semi-major axis = 35 mas (typical of TPF-I targets – see slide 12)
- Broadband 7 – 17 um, co-added maps
- No noise
- Angular resolution is insufficient to separate the planets
Angular resolution criterion

- FWHM of main peak of PSF @ 10 um \(\leq 0.5 \times \) radius of IHZ
- More robust deconvolution and reduced risk of spectral contamination

- Requires increase in array size to 128 m for Linear 3
Impact of larger array size

- Increased stellar leakage
- Stray light constraint rules out more stars

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Increase in array size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear DCB A</td>
<td>x 4.2</td>
</tr>
<tr>
<td>Linear DCB B</td>
<td>x 1.35</td>
</tr>
<tr>
<td>X-Array 2:1</td>
<td>x 1.2</td>
</tr>
<tr>
<td>Diamond DCB</td>
<td>x 2.2</td>
</tr>
<tr>
<td>Z-Array</td>
<td>x 1.0</td>
</tr>
<tr>
<td>Triangle</td>
<td>x 2.0</td>
</tr>
<tr>
<td>Linear 3</td>
<td>x 2.8</td>
</tr>
</tbody>
</table>
The Sun @ 10 pc is not typical…

The diagram shows a scatter plot with the x-axis representing Projected IHZ / mas and the y-axis representing Distance / pc. The data points are color-coded to indicate different categories: All (1014), <24 hrs (234), <16 hrs (171), <8 hrs (89), <4 hrs (51), and <2 hrs (26). The Sun @ 10 pc is marked as a typical target.