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TPF Terrestrial Planet Finder Interferometer

Architecture Trade Study for the Terrestrial Planet Finder Interferometer

JPL

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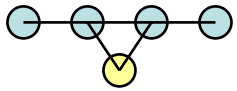
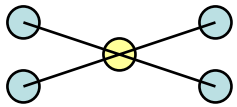
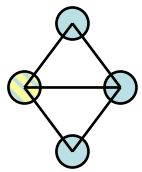
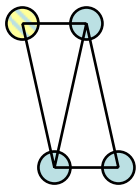
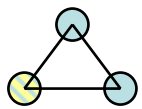
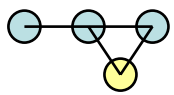
Introduction

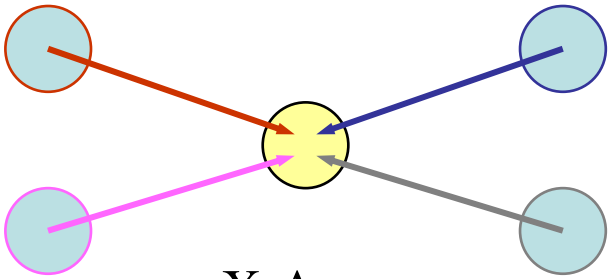
- A systematic, quantitative comparison of leading architectures
- Architecture = # collectors & combiners, geometric nulling config, aperture size, # launches
- 6 basic options, judged against ~45 metrics
- Select best architecture for detailed interim study by Design Team
- Completed in December 2004
- Not the final architecture for TPF-I!

Nulling configurations

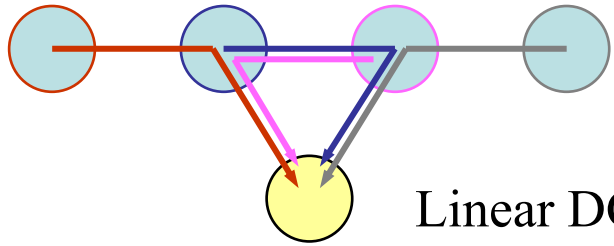
- Linear DCB 
- X-Array 
- Diamond DCB 
- Z-Array 
- Triangle 
- Linear 3 

- Not considered:
  - θ^4 nulls
  - Single Bracewell
  - Structurally-connected
- Common themes
  - All θ^2 null
  - All <= 5 spacecraft
  - Dual Chopped Bracewell family

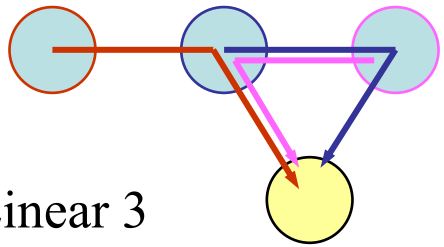
Constraints: delay equalization



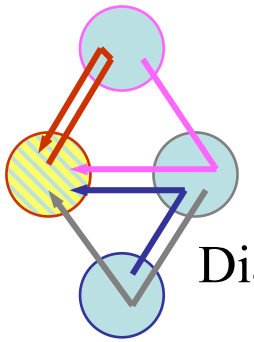
X-Array



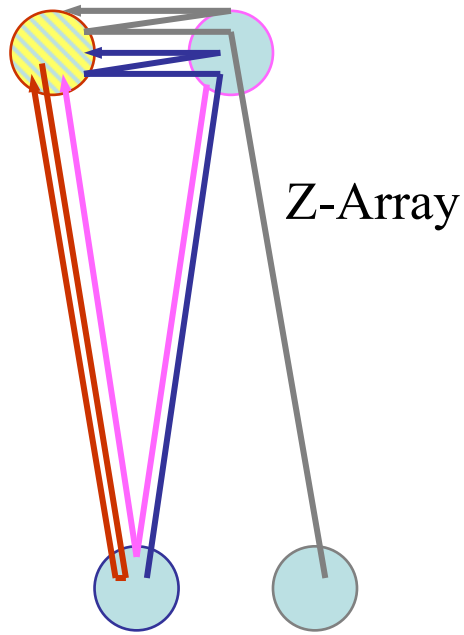
Linear DCB



Linear 3

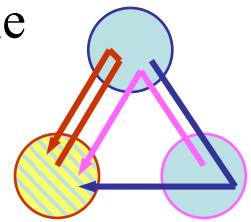


Diamond DCB



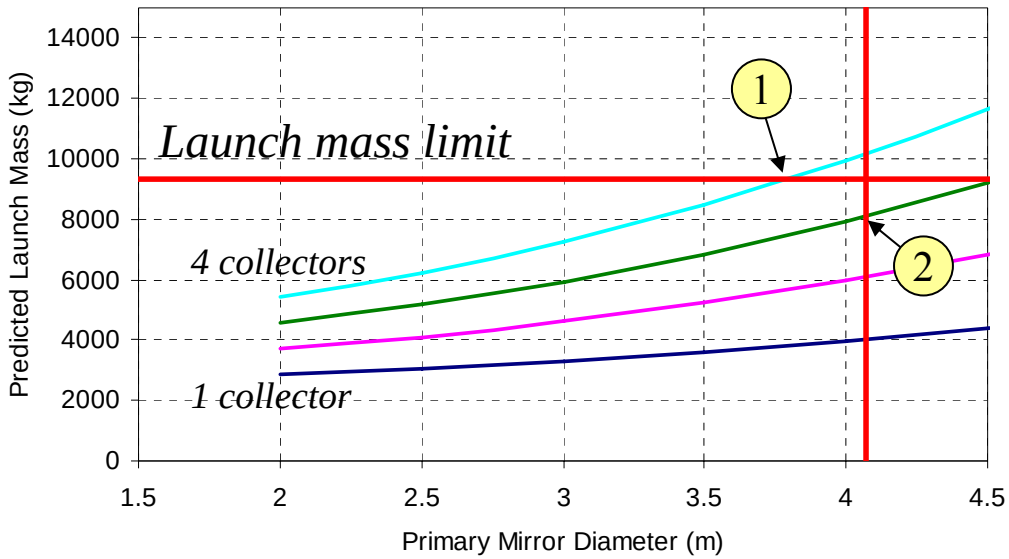
Z-Array

Triangle



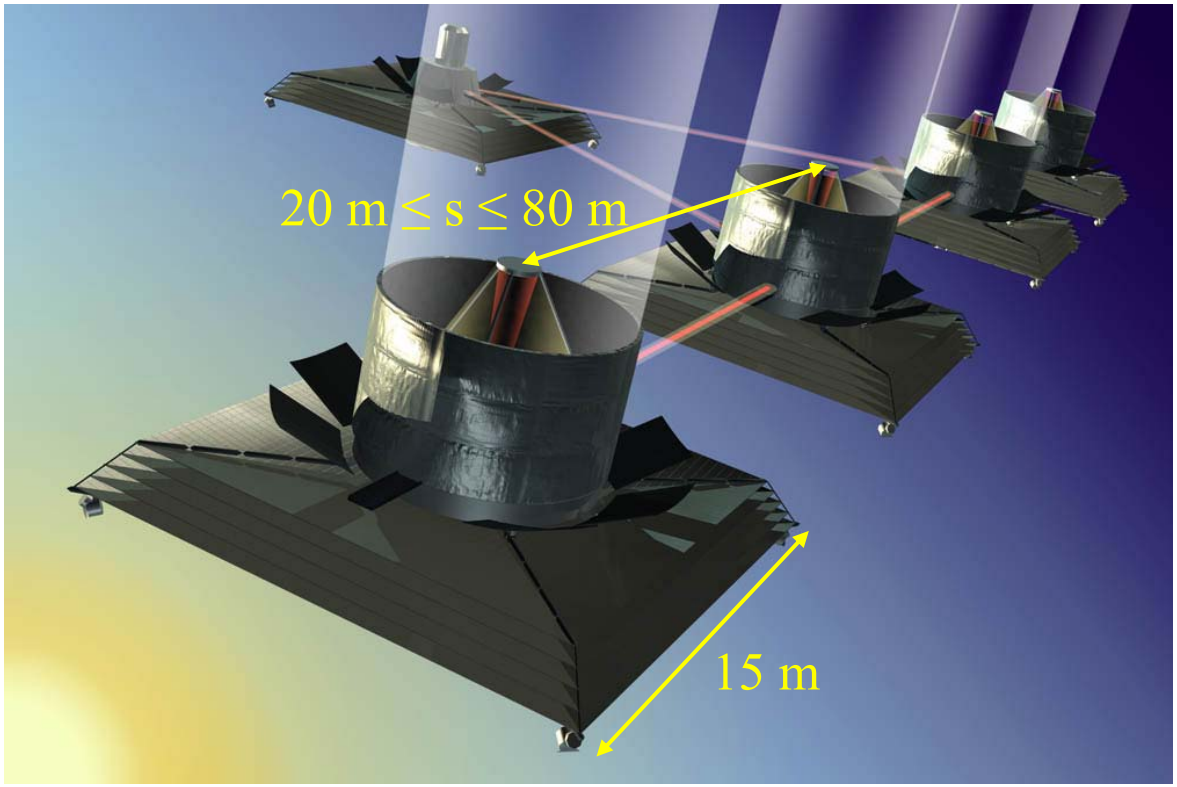
Constraints: aperture size

- 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



	Config	# spacecraft # comb	# spacecraft # coll	D / m	Constraint
1	Linear DCB	1	4	3.8	Mass
	X-Array	1	4	3.8	Mass
	Diamond DCB	0	4	4.1	Fairing diam.
	Z-Array	0	4	4.1	Fairing diam.
2	Linear 3	1	3	4.1	Fairing diam.
	Triangle	0	3	4.1	Fairing diam.

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

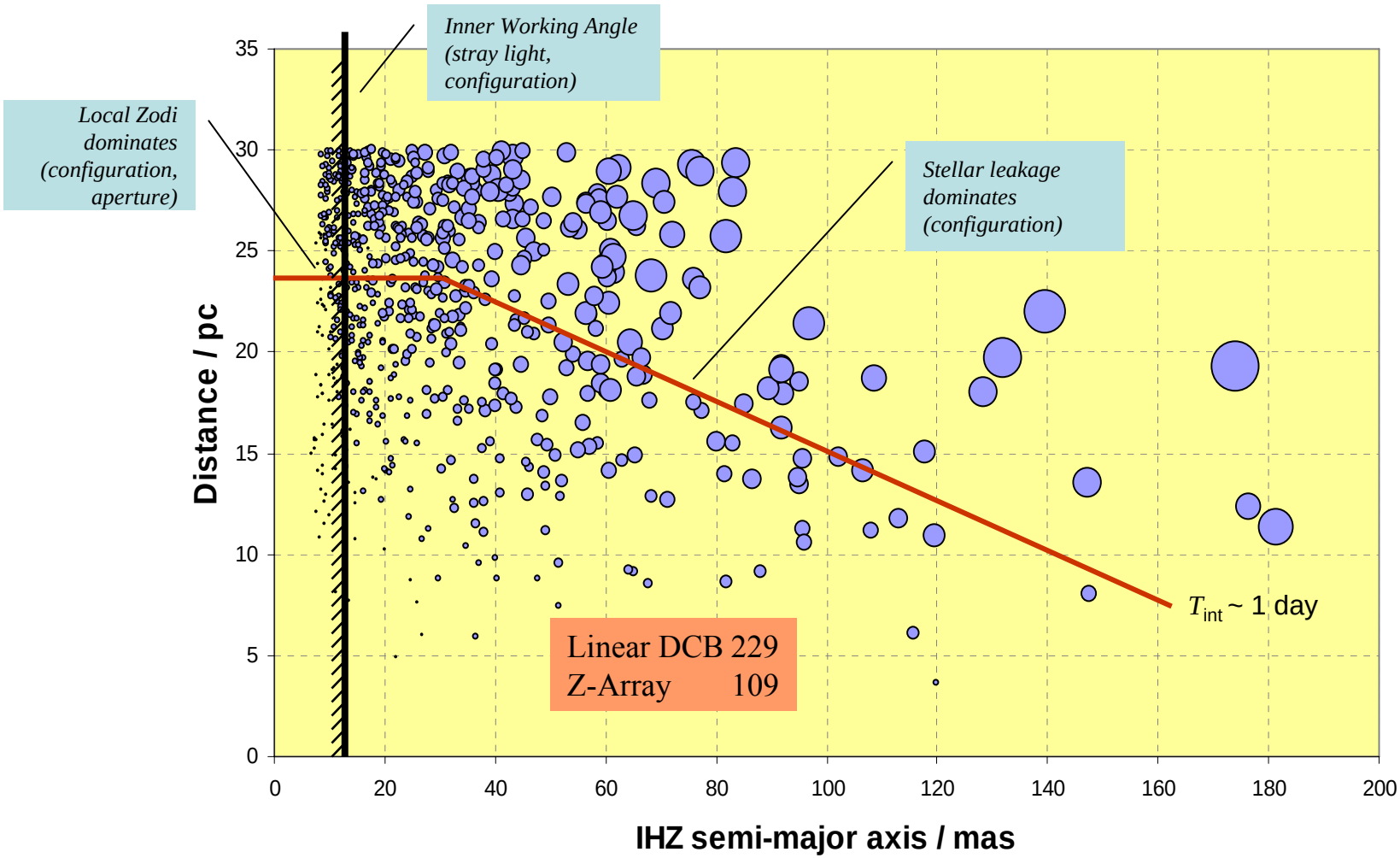
Process

- 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

Choose the TPF-I architecture for further study				Options													
	Metric	Name		Linear DCB		X-Array (2:1)		Diamond DCB		Z-Array		Triangle		Linear 3		Linear DCB		X-Array (2:1)	
		# launches		1				1		1		1		1		2		2	
		Aperture		2.6 m		3.6 m		4.1 m		4.1 m		4.1 m		4.1 m		4.1 m		4.1 m	
		Min size		60 m		60 m		35 m		66 m		20 m		40 m		60 m		66 m	
		Max size		240 m		160 m		139 m		89 m		80 m		160 m		240 m		160 m	
		Collector mass		1097 kg		1097 kg		1232 kg		1232 kg		1232 kg		1232 kg		1232 kg		1232 kg	
		Combiner mass		1175 kg		1175 kg		356 kg		356 kg		356 kg		1175 kg		1175 kg		1175 kg	
		Sub-config		Lo-res	Hi-res	1:1	3:1	N/A		N/A		N/A		N/A		Lo-res	Hi-res	1:1	3:1
		Avg resolution tol (λ_0)		0.67	0.40	0.80	0.97	0.65		0.92		1.00		0.60		0.67	0.40	0.80	0.97
		FWHM (λ / λ_0)		0.75	1.25	0.63	0.52	0.77		0.54		0.50		0.83		0.75	1.25	0.63	0.52
		Lo-res IWA (λ / λ_0)		1.10	0.60	0.55	1.25	0.70		1.30		0.50		0.60		1.10	0.60	0.55	1.25
		Hi-res IWA (λ / λ_0)		1.49	2.50	1.25	1.25	1.54		1.38		1.00		1.67		1.49	2.50	1.25	1.25
		Mod. Eff.		0.22	0.26	0.22	0.22	0.22		0.22		0.20		0.26		0.22	0.26	0.22	0.22
		Stellar leak param		0.056	0.220	0.250	0.650	0.167		0.045		0.075		0.167		0.056	0.220	0.250	0.650
MUST																			
Number of stars surveyed (detection) > 100	Star count	y / n		y	229	y	157	y	185	y	109	y	115	y	170	y	260	y	178
Number of stars characterized (spectroscopy) > 5 (100 x 10% x 50%)	Star count	y / n		y	14.2	y	13.9	y	8.8	y	9.1	n	2.5	n	3.7	y	16.1	y	15.7
Symmetric Exo-zodi suppression		y / n		y		y		y		y		y		y		y		y	
Instrument background suppression		y / n		y		y		y		y		y		y		y		y	
Detect Jupiters at 5 au around 50% the stars		y / n		y		y		y		y		y		y		y		y	
Mass margin > 20%		y / n		y	30%	y	30%	y	33%	y	33%	y	46%	y	37%	y	50%	y	50%
Feasible beamcombiner		y / n		y		y		y		y		y		y		y		y	
Feasible control system		y / n		y		y		y		y		y		y		y		y	
WANT		Weight	Sub-weight																
Performance																			
Number of stars surveyed (beyond minimum required)	Star count	4.9	1	9.4	229	7.5	157	8.9	185	0.7	109	0.8	115	8.3	170	10.0	260	8.5	178
Number of stars located < 5 pc that can be surveyed	Star count	3.4	1	10.0	All	10.0	All	10.0	All	10.0	All	10.0	All	10.0	All	10.0	All	10.0	All
Number of stars on the coronagraph's list that can be surveyed	Star count	5.6	1	10.0	All	10.0	All	10.0	All	10.0	All	10.0	All	10.0	All	10.0	All	10.0	All
Number of planet systems characterized by spectroscopy at high angular resolution, beyond minimum required	Star count	5.4	1	4.2	14.2	4.5	13.9	2.0	8.8	2.2	9.1	0.0	2.5	0.0	3.7	5.2	16.1	5.0	15.7
Number of planet systems characterized by spectroscopy at low angular resolution, beyond minimum required	Star count	2.2	1	8.3	22.5	4.8	15.1	6.3	18.2	2.0	9.1	2.7	10.4	5.2	16.2	10.0	25.7	6.0	17.3
Fidelity of image reconstruction		5.7	1	7.2		7.6		6.8		6.1		4.5		7.0		7.2		7.6	
	Peak/peak (in Point Spread Function for planet at high raw linear working angle)		0.5	**10.0**	5.30%	9.3	5.85%	8.0	6.8%	7.1	7.5%	**5.0**	9.1%	8.4	6.5%	10.0	5.30%	9.3	5.85%
	FWHM of main peak (in Point Spread Function for planet at 36 max high res inner working angle)		0.3	7.2	24	**10.0**	20	9.3	21	8.6	22	**6.5**	25	9.3	21	7.2	24	10.0	20
	# main peaks in PSF		0.2	10.0	1	**10.0**	1	10.0	1	10.0	1	**5.0**	3	10.0	1	10.0	1	10.0	1
Calibration time	# collectors	4.4	1	8.5	4	8.5	4	8.5	4	8.5	4	**10.0**	3	10.0	3	8.5	4	8.5	4
Ability to suppress non-symmetric star features	IWA / FWHM beam size (for high resolution case, 60 um)	3.3	1	8.0	2.0	10.0	2.4	8.0	2.0	10.0	2.4	8.0	2.0	8.0	2.0	8.0	2.0	10.0	2.4
General astrophysics potential		4.4	1	9.8		8.6		8.1		5.8		5.9		8.1		9.8		8.6	
	Dynamic range of baselines (max/min)		0.3	**10.0**	12	7.0	8	6.3	7	**2.0**	1.3	4.0	4	7.0	8	10.0	12	7.0	8
	Maximum angular resolution at 10 um (mas)		0.3	**10.0**	4.3	8.3	6.4	7.5	7.4	4.1	11.6	**3.0**	12.9	8.3	6.4	10.0	4.3	8.3	6.4
	no. of distinct simultaneous baselines		0.1	7.5	3	**10.0**	4	10.0	4	10.0	4	7.5	3	**5.0**	2	7.5	3	10.0	4
	N/A		0.3	10.0		10.0		10.0		10.0		10.0		10.0		10.0		10.0	
Cost and Risk																			
Number of types of spacecraft	# types	4.7	1	7.0	3	10.0	2	7.0	3	5.0	4	7.0	3	7.0	3	7.0	3	10.0	2
Number of spacecraft	# spacecraft	2.6	1	6.5	5	6.5	5	8.0	4	8.0	4	10.0	3	8.0	4	6.5	5	6.5	5
Number of launches	# launches	8.7	1	10.0	1	10.0	1	10.0	1	10.0	1	10.0	1	10.0	1	5.0	2	5.0	2
Mass margin	Mass margin	2.6	1	3.0	30%	**3.0**	30%	4.1	33%	4.1	33%	8.6	46%	5.5	37%	**10.0**	50%	10.0	50%
Equal size collector primaries	# distinct primary diameters	2.7	1	10.0	y	10.0	y	10.0	y	10.0	y	10.0	y	10.0	y	10.0	y	10.0	y
Beam transport optics complexity		4.1	1	7.0		10.0		7.0		4.5		7.0		7.0		7.0		10.0	
	# hops to combiner		1	7.0	2 hops	10.0	1 hop	7.0	2 hops	4.5	4 hops	7.0	2 hops	7.0	2 hops	7.0	2 hops	10.0	1 hop
	Variable angles		0	10.0	n	10.0	n	10.0	n	10.0	n	10.0	n	10.0	n	10.0	n	10.0	n
	Optical switch needed?		0		y	10.0	n	10.0	n	10.0	n	10.0	n	10.0	n	10.0	y		n
Control system complexity	# control loops	4.8	1	8.3	22	**10.0**	18	8.3	22	**6.5**	26	9.6	19	9.6	19	8.3	22	10.0	18
Beamcombiner optics complexity		4.1	1	10.0	4-way	10.0	4-way	10.0	4-way	10.0	4-way	6.5	3-way	6.5	3-way	10.0	4-way	10.0	4-way
	Can it use 0 and 180 deg shears for nulling?		0.5	10.0	y	10.0	y	10.0	y	10.0	y	8.0	n	8.0	n	10.0	y	10.0	y
	# parts (from schematic)		0.5	10.0		10.0		10.0		10.0		5.0		5.0		10.0		10.0	
Redundancy / graceful degradation		4.3	1	8.4		9.9		3.8		6.9		4.3		5.0		8.4		9.9	
	Expected % of optimal		0.5	8.9	77%	9.8	81%	**7.5**	71%	8.9	77%	8.6	76%	**10.0**	82%	8.9	77%	9.8	81%
	Expected % of stars observed after loss of 1 spacecraft		0.5	8.0	16%	10.0	22%	0.0	0%	5.0	9%	0.0	0%	0.0	0%	8.0	16%	10.0	22%
Number of mechanisms/ moving parts	# mechanisms / deployments	3.7	1	7.0	47	7.0	47	8.0	42	8.0	42	10.0	32	8.0	42	7.0	47	7.0	47
Difficulty of thermal control system		2.6	1	5.9		8.4		5.3		4.4		7.3		7.5		5.9		8.4	
	# active sensors/mechanisms on bent side (same collector)		0.375	6.3	9	**10.0**	5	6.3	9	**2.5**	13	6.3	9	6.3	9	6.3	9	10.0	5
	# active sensors/mechanisms on bent side (combiner)		0.375	6.3	36	6.3	36	4.2	41	**2.5**	45	7.9	32	**10.0**	27	6.3	36	6.3	36
	proximity factor		0.25	**5.0**	3.25	9.0	1.61	5.6	3	**10.0**	1.22	8.1	2	5.6	3	5.0	3.25	9.0	1.61
Difficulty of integration and test		4.4	1	4.7		5.3		6.6		6.2		9.2		6.6		4.5		5.0	
	# spacecraft		0.55	3.0	5	3.0	5	6.0	4	6.0	4	10.0	3	6.0	4	3.0	5	3.0	5
	# spacecraft needed for end-to-end beam train		0.15	6.0	3	10.0	2	6.0	3	6.0	3	6.0	3	6.0	3	6.0	3	10.0	2
	Collector aperture		0.15	10.0	3.8 m	10.0	3.8 m	8.5	4.1 m	8.5	4.1 m	8.5	4.1 m	8.5	4.1 m	8.5	4.1 m	8.5	4.1 m
	Minimum array length (5 x separation + 5 m)		0.15	4.5	20	**4.0**	21	7.8	14	4.5	20	**10.0**	10	7.3	15	4.5	20	4.0	21
Complexity of flight operations		2.6	1	5.4		5.4		7.0		7.0		10.0		7.6		5.4		5.4	
	# spacecraft		0.60	5.0	5	5.0	5	7.0	4	7.0	4	10.0	3	7.0	4	5.0	5	5.0	5
	# collectors		0.20	7.0	4	7.0	4	7.0	4	7.0	4	10.0	3	10.0	3	7.0	4	7.0	4
Fuel usage	sum of (mass * radius) for nominal observation	1.7	1	6.2	201.5	8.7	157	7.4	180	7.1	186	**10.0**	134	8.5	161	**5.0**	222.5	7.6	177
Complexity of inter-SIC comm. & coarse formation sensing		1.2	1	6.1		6.5		8.3		7.3		10.0		7.9		6.1		6.5	
	# spacecraft		0.70	5.0	5	5.0	5	7.5	4	7.5	4	10.0	3	7.5	4	5.0	5	5.0	5
	combiner-collector dynamic range (10 km max)		0.10	10.0	500	10.0	500	10.0	500	10.0	500	10.0	500	10.0	500	10.0	500	10.0	500
	instantaneous combiner-collector dynamic range		0.20	8.0	1.73	10.0	1	10.0	1	5.0	3	10.0	1	8.0	1.73	8.0	1.73	10.0	1
Adaptability to pre-launch predictions of $\eta_\oplus$ of Earths		2.2	1	8.8		7.2		6.9		4.9		3.9		7.1		9.3		7.5	
	Dynamic range of baselines		0.25	**10.0**	12	7.0	8	6.3	7	**2.0**	1.3	4.0	4	7.0	8	10.0	12	7.0	8
	Maximum angular resolution at 10 um		0.25	**10.0**	4.3	8.3	6.4	7.5	7.4	4.1	11.6	**3.0**	12.9	8.3	6.4	10.0	4.3	8.3	6.4
	Imaging fidelity		0.25	7.2		7.6		6.8		5.1		4.5		7.0		7.2		7.6	
	Sensitivity factor		0.25	8.2	16.2	5.8	12.7	7.2	14.8	7.2	14.8	**4.0**	10.1	6.1	13.1	**10.0**	18.8	7.2	14.8
Concept Maturity		2.3	1	10.0		8.5		8.0		6.0		6.0		6.5		9.5		8.0	
Legacy (technology useful to future missions)		1.6	1	10.0		10.0		10.0		10.0		10.0		10.0		10.0		10.0	
	Overall score / 1000			**793**		**828**		**762**		**676**		**725**		**759**		**776**		**810**	
	Performance			323		312		295		239		220		286		335		322	
	Cost / risk			470		517		467		437		505		473		441		488	

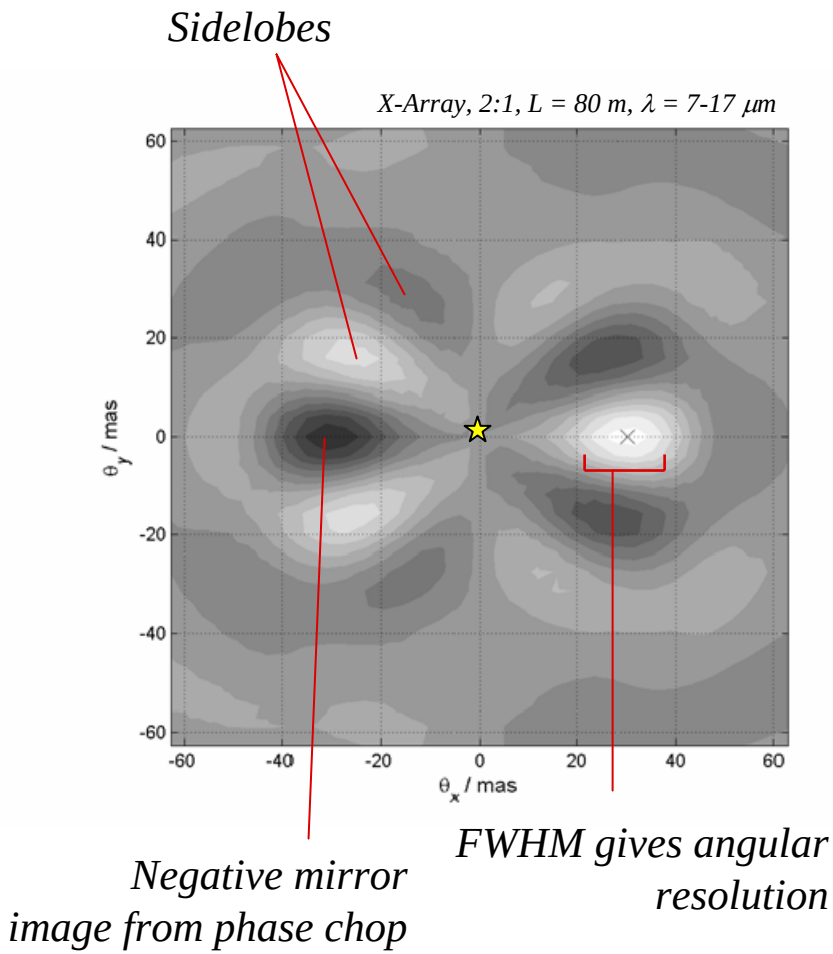
Performance: observable stars (21.5%)

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



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)

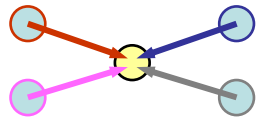
- Control system complexity (4.8%)
  - # control loops (ranged from 18 to 26)

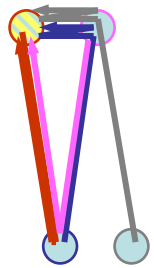
- # different types of spacecraft (4.7%)
  - Non-recurring costs are expected to be major driver

- 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





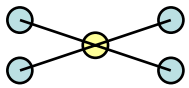
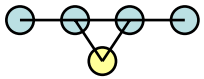
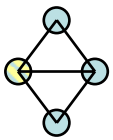
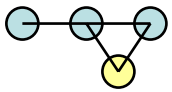
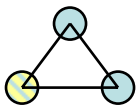
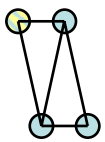
- Beam combiner complexity (4.1%)
  - # parts needed
  - Requires achromatic phase shifts other than 0 or 180 deg?

- # 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%)

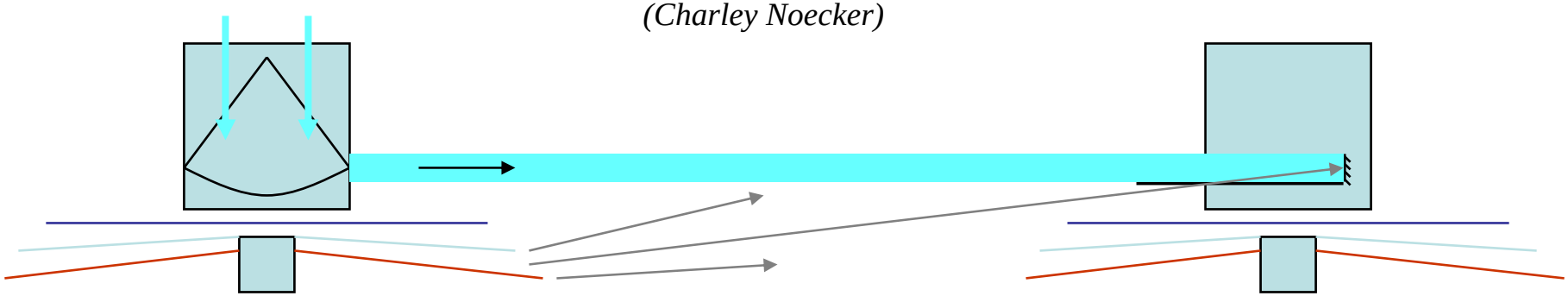
Results

		Score /1000	Pros	Cons
X-Array		841	▪ 2 types of spacecraft (+14) ▪ Simple beam relay (+12) ▪ Degrades gracefully (+6)	▪ # Stars surveyed (-9) ▪ General Astrophysics (-7)
Linear DCB		805	▪ # stars surveyed ▪ Spectroscopy performance	▪ # spacecraft ▪ Mass margin ▪ Ease of I&T
Diamond DCB		774	▪ Ease of I&T (+8) ▪ # mechanisms (+4) ▪ # spacecraft (+4)	▪ Graceful degradation (-17) ▪ Spectroscopy performance (-16) ▪ General Astrophysics (-7)
Linear 3*		772	▪ Ease of I&T (+8) ▪ Calibration time (+7) ▪ Mass margin (+6)	▪ Spectroscopy performance (-30) ▪ Redundancy (-15) ▪ Beam combiner complexity (-14)
Triangle*		731	▪ Ease of I&T (+20) ▪ Mass margin (+15) ▪ Flight operations (+12)	▪ # Stars surveyed (-42) ▪ Spectroscopy performance (-35) ▪ General Astrophysics (-17)
Z-Array		689	▪ Ease of I&T (+6) ▪ # mechanisms (+4) ▪ # spacecraft (+4)	▪ # Stars surveyed (-43) ▪ Spectroscopy performance (-25) ▪ General Astrophysics (-17)

Update to SPIE paper

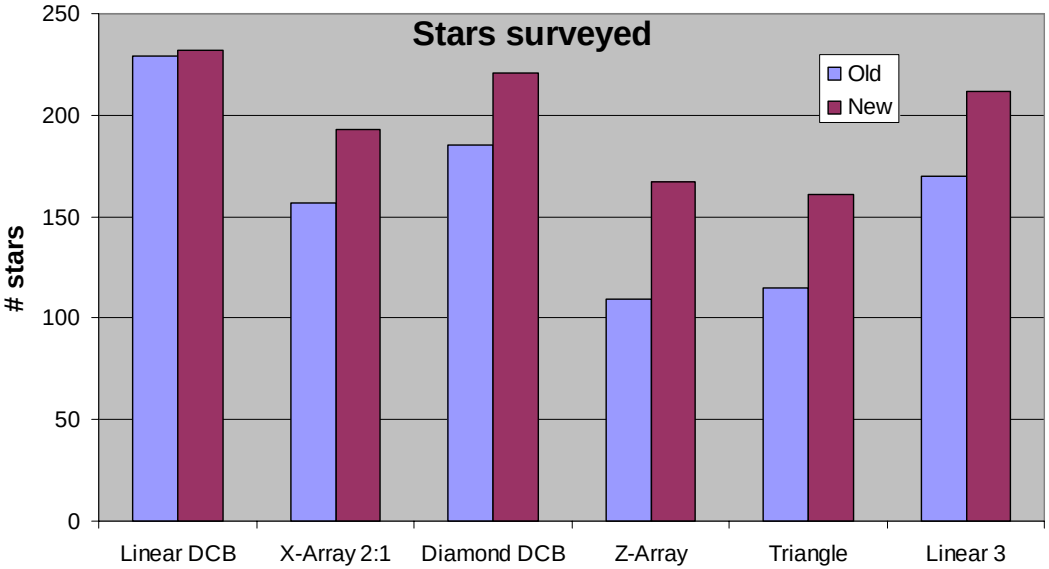
Max array size update

Thermal stray light problem
(Charley Noecker)

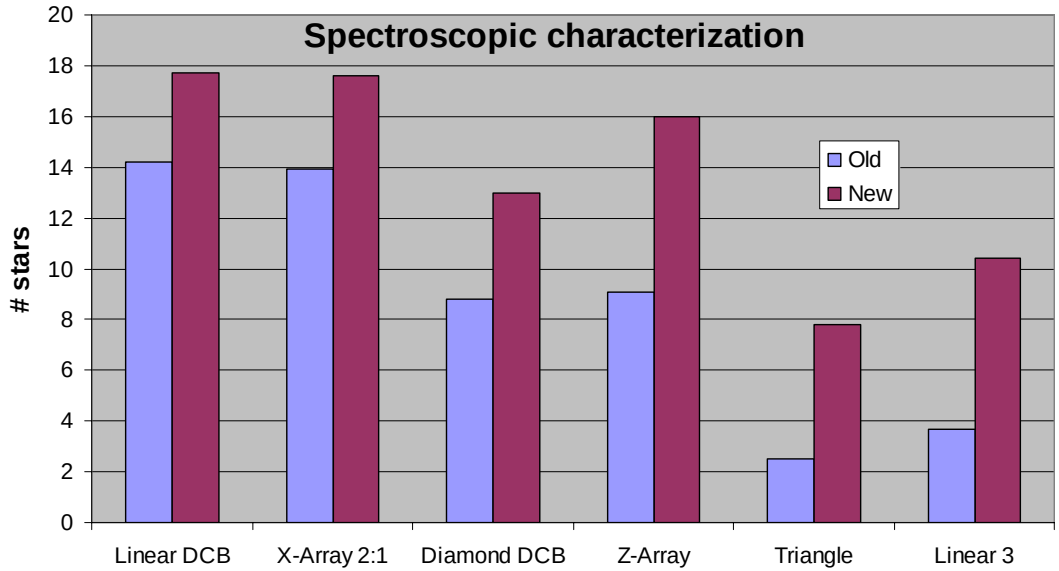


- For trade study, max. separation = 80 m
- Following an optimization of the beam transport, max. separation = 165 m
- Leads to doubling of max. array size for each configuration

Impact on star counts

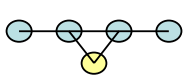
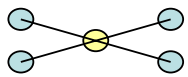
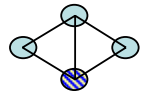
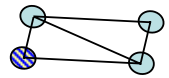
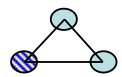
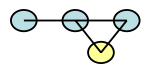


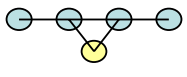
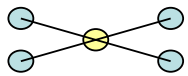
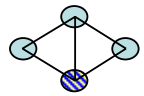
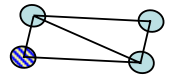
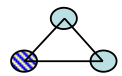
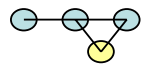
- Little change to Linear DCB
  - Not limited by IWA during survey
- 50% increase for Z-Array
  - Previously most constrained by stray light



- 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

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

Old	Linear DCB	X-Array (2:1)	Diamond DCB	Z-Array	Triangle	Linear 3
						
Overall score / 1000	**805**	**841**	**774**	**689**	**731**	Failed	**772**	Failed
Performance	370	365	323	280	244	319
Cost / risk	435	475	452	408	487	452

- 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

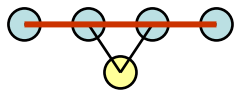
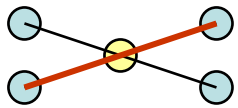
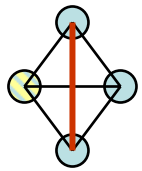
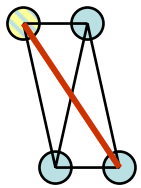
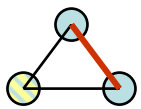
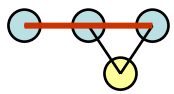
Conclusions

- 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

Min Array size

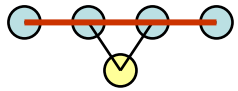
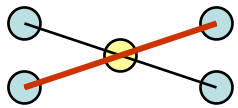
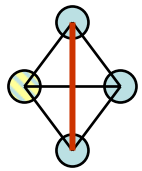
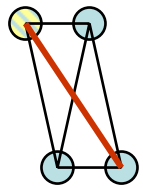
- Linear DCB  60 m
- X-Array  40 m
- Diamond DCB  35 m
- Z-Array  66 m
- Triangle  20 m
- Linear 3  40 m

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

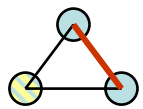
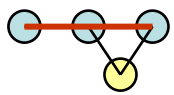
Increased integration time for nearby stars

Constraints: stray light

Max Array size

- Linear DCB  240 m
- X-Array  160 m
- Diamond DCB  140 m
- Z-Array  88 m*

* $L_{max} < L_{min}$ (66 m)

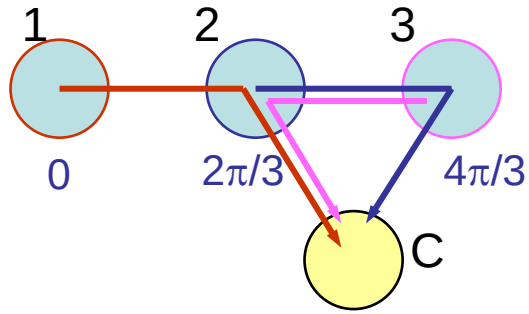
- Triangle  80 m
- Linear 3  160 m

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

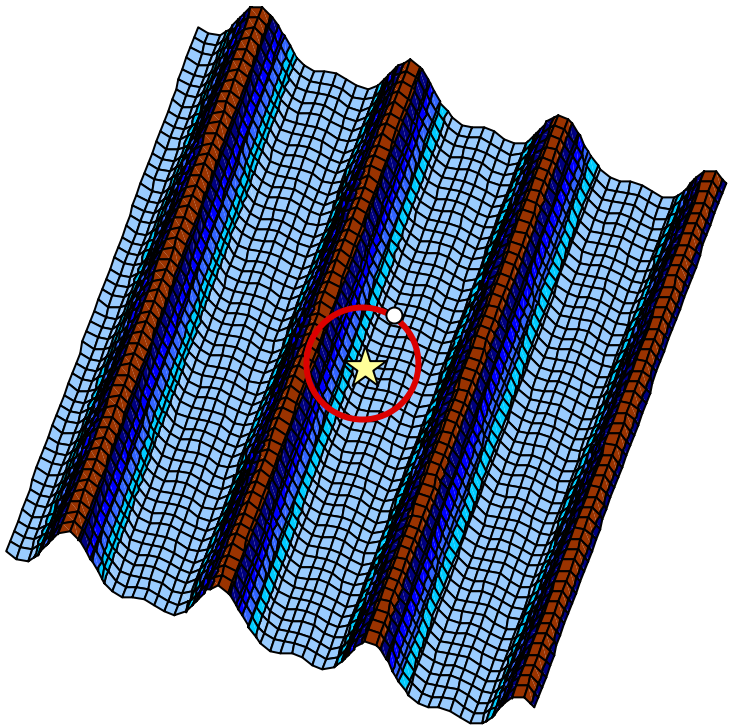
Limits Inner Working Angle

Inner Working Angle

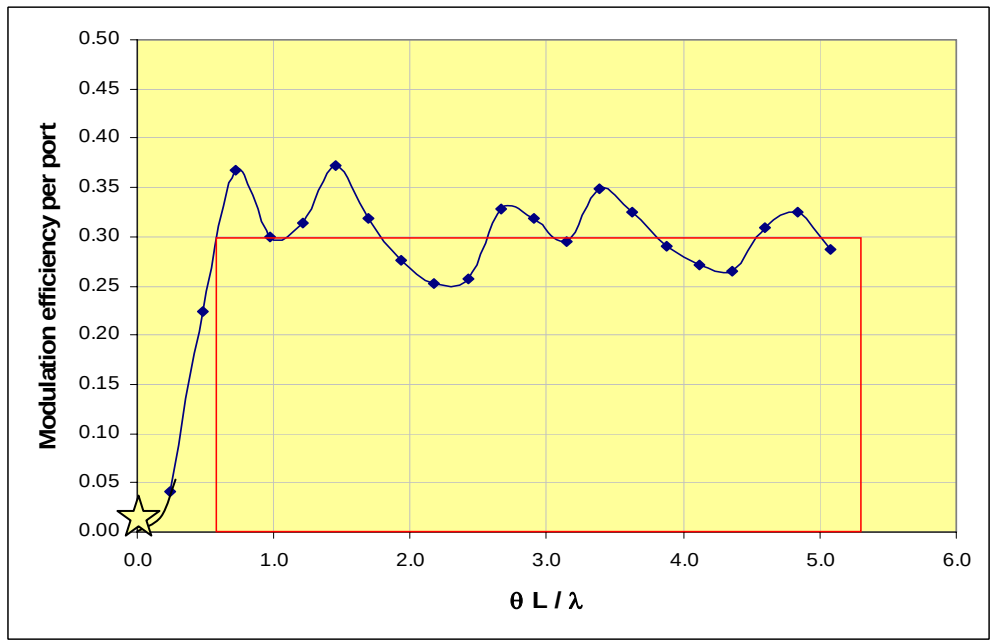
- Example: Linear 3 configuration



- "Put the planet on the first fringe"

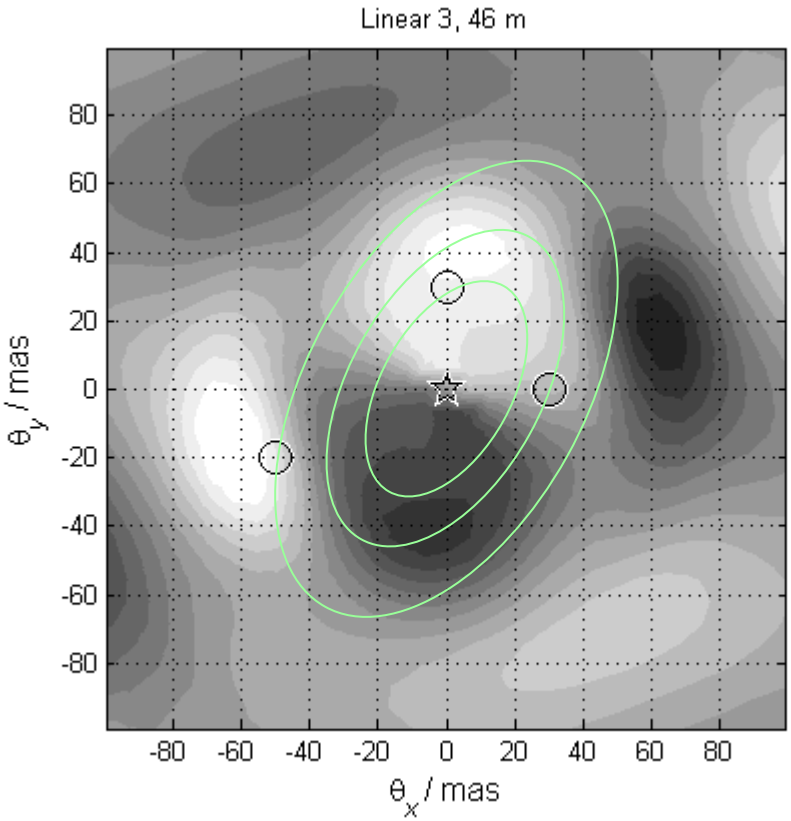


- More sophisticated version from modulation efficiency curve:



- IWA = 27 mas @ 10 um => L = 46 m

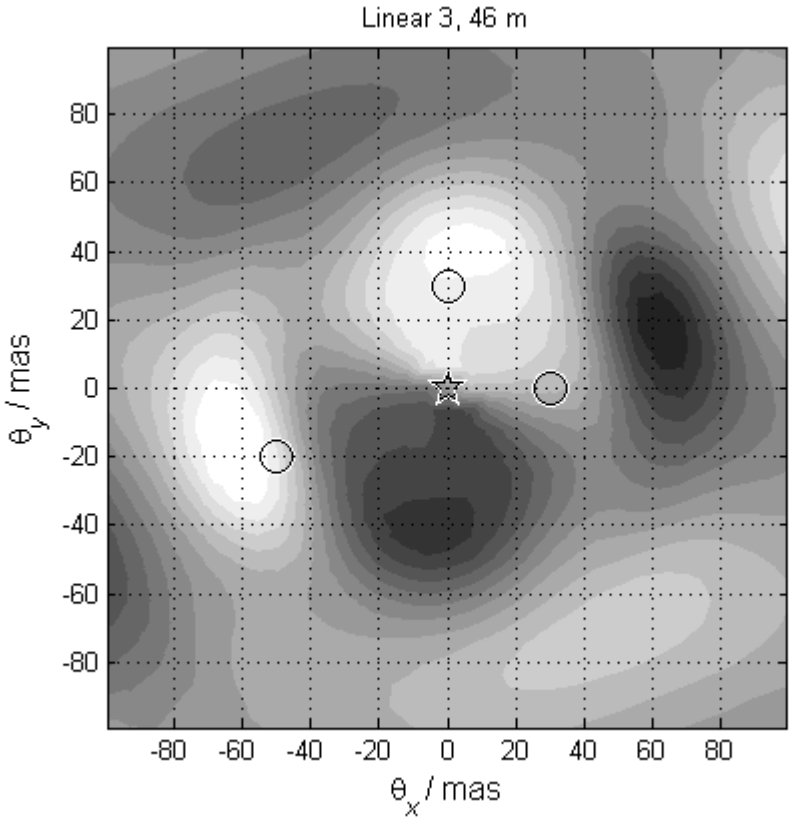
Linear 3, dirty map

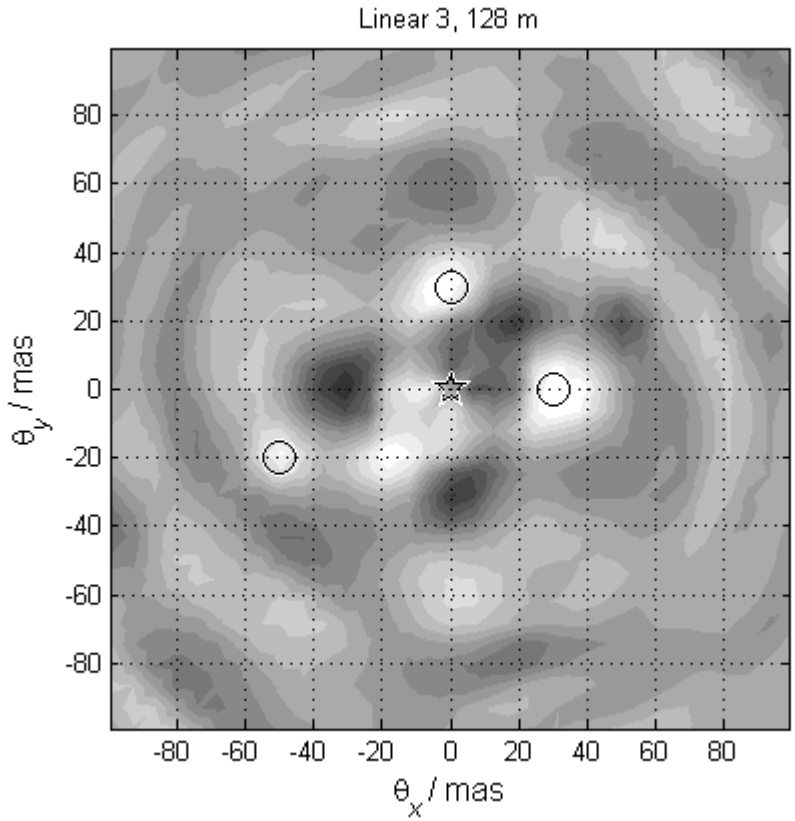


- Linear 3, 46 m baseline
- Venus – Earth – Mars orbits, equal flux
- IHZ semi-major axis = 35 mas (typical of TPF-I targets – see slide 12)
- Broadband 7 – 17 um, co-added maps
- No noise
- Angular resolution is insufficient to separate the planets

Angular resolution criterion

- FWHM of main peak of PSF @ 10 um ≤ 0.5 x 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

Configuration	Increase in array size
Linear DCB A	x 4.2
Linear DCB B	x 1.35
X-Array 2:1	x 1.2
Diamond DCB	x 2.2
Z-Array	x 1.0
Triangle	x 2.0
Linear 3	x 2.8

The Sun @ 10 pc is not typical…