TRW Space & Electronics Group

Architecture Comparisons

Stewart Moses

Our Evaluations Showed Viability of Non-Interferometric Architectures

TRW

- Our assessments use JPL ranking criteria to develop an overall system utility function
  - Science Utility
  - Technical Risk
  - Reliability/Robustness
  - Legacy (Heritage to Future Origins Missions)
- The overall comparison ranked system against cost
- Results showed that a number of direct imaging systems might provide good system utility at less cost than nulling interferometers
- Further work is needed to refine our estimates of system utility for the non-interferometric and perform a more evenly weighted comparison of all architectures

Science Utility Based on Ability to Perform TPF and Other Astronomy

TRW

- TPF mission consists of investigations needed to identify and characterize exo-solar planets
  - Additional science utility for TPF mission consists of detecting planets in a larger variety of exo-zodi conditions
  - Additional science utility for other astronomy based on the ability to perform imaging and spectroscopy on a variety of different types of targets

We Have Performed a Relative Ranking of Measurement Techniques

TRW

- Techniques normalized to detect median target
- All nulling interferometer implementations are considered the same measurement technique
- Additional astrophysical targets are classed as either unresolved point sources or resolved continuous objects

TRW

Science Utility Assessments

Investigation	Evaluation Criteria	NI	LAC	FL	ULSA	FFO	Comments
Exo-Planet Detection	Ability to determine orbit	M	M	M	H	M	• ULSA benefits from high angular resolution
	Ability to overcome confusion due to exo-zodi structrue	L	M	M	H	H	• Confusion limited by larger imaging apertures • FFO sees less confusion operating in visible
	Ability to handle multiple planets viewed simultaneously	L	M	M	H	M	• Interferometers perform less well with multiple planets
	Ability to handle high exo-zodi density	L	M	M	H	H	• Large apertures less effected by exo-zodi noise • Smaller problem in visible for FFO
Exo-Planet Characterization	Ability to determine planet temperature	H	H	H	M	L	• ULSA operates at shorter infrared wavelengths • FFO operates in visible
	Ability to determine atmospheric composition	M	H	H	H	M	• Large apertures have good spectroscopic capability • FFO misses some absorption lines
Other Astrophysics	Ability to image multiple point sources	M	M	M	H	M	• ULSA benefits from high resolution and good uv-plane coverage
	Ability to image extended, low-contrast targets	L	M	M	M	M	• NI do not perform as well with low-contrast
	Ability to perform general spectroscopy	M	M	M	H	M	• ULSA benefits from large collecting area

Science Utility Rankings

Architecture	Rank	Highs	Mediums	Lows
ULSA	25	7	2	0
LAC	20	2	7	0
FL	20	2	7	0
FFO	19	2	6	1
NI	15	1	4	4

Architectures Are Given a Relative Risk Ranking

- Key technologies assessed for their technical risks
- Architectures ranked based on the number and severity of risks

Risk Evaluation Criteria

Ranking	Criteria
NA	• Architecture does not rely on this technology
Low	• Technology already exists in the form required for this architecture • Technology requires a moderate scaling to meet architecture requirements (e.g. the technology needs to be made twice as large) • Technology is being developed on another program to the level required by this architecture
Medium	• Technology needs to be adapted to work in another environment (e.g. the technology needs to made to operate at cryogenic temperatures) • Technology requires a significant rescaling to meet architecture requirements (e.g. the technology needs to be made ten times as large) • Technology is not being developed on another program to the level required by this architecture
High	• There is no existing technology path to meet architecture requirements • Technology requires a major rescaling to meet architecture requirements (e.g. the technology needs to be made one hundred times as large) • Technology size or complexity severely impacts the ability to test the architecture

Terms Definitions

NI(FF)	• Formation flying implementation of nulling interferometer
NI(M)	• Monolithic structure implementation of nulling interferometer
LAC	• Large aperture with coronagraph
FL	• Fresnel lens
ULSA	• Ultra-large sparse aperture
FFO	• Free-flying occulter
Optics	• Includes collecting optics, both reflective and transmissive • Include devices to control pathlength, wavefront, etc. • Does not include the occulter in the FFO • Does include the Fresnel lens elements
Flight system	• Includes spacecraft subsystems • Includes structures for supporting instrumentation • Include FFO occulter structure • Includes thermal control and dynamic control

Optics Technology Assessments

Technology	NI(FF)	NI(M)	LAC	FL	ULSA	FFO	Comments
Mirror material technology	L	L	M	L	L	M	• LAC requires lightweight beyond NGST • FL silicon lens not flown in space
Mirror figure control	L	L	L	L	L	M	• FFO requires better than NGST figure control
Downstream optics	M	M	L	L	M	L	• NI needs SIM type optics to operate at cryogenic • ULSA needs very large optics
Coronagraph technology	NA	NA	M	M	L	NA	• LAC and FL need advanced appodized occluding spot • ULSA needs simple occluding spot
Pathlength control	M	M	NA	NA	NA	NA	• NI need SIM level control to operate at cryogenic
Polarization control	M	M	NA	NA	NA	NA	• NI need SIM level control to operate at cryogenic
Beam intensity control/beam spitting	M	M	NA	NA	NA	NA	• NI need SIM level control to operate at cryogenic
Transmissive material technology	NA	NA	NA	M	NA	M	• FL silicon lens material being developed • Material development for FFO transmissivity requirements
Optics deployment technology	L	L	M	M	L	L	• NI, ULSA, and FFO can use NGST technology if needed • LAC must rescale NGST technology • FL may need to deploy lens
Metrology	M	M	L	L	M	L	• NI require SIM metrology at cryogenic • ULSA requires metrology between large primary and eyepiece
Assembly in space	NA	NA	NA	M	M	NA	• FL lens, ULSA may require on orbit assembly

TRW

Flight System Technology Assessments

Technology	NI(FF)	NI(M)	LAC	FL	ULSA	FFO	Comments
Thermal control	M	L	L	L	M	L	• NI(FF) and ULSA require shielding between neighbors
Attitude control	M	M	M	M	M	M	• Most require control of large structures
Alignment of optical elements	M	L	L	M	M	L	• Multiple spacecraft alignments
Dynamics control	L	M	M	L	M	M	• NI(M), LAC, FFO require dynamics control of large structures
Precision station keeping	M	NA	NA	M	M	M	• NI and FL need ST-3 station keeping of larger elements or over longer ranges • FFO needs station keeping over very large ranges
Formation initialization	M	NA	NA	M	M	M	• Formation initialization complexity ranked on an individual spacecraft basis
Deployable structures	L	M	M	L	M	M	• NI(M), LAC, ULSA, FFO will need deployment of large shades/baffles
Operational complexity	M	L	L	M	M	M	• NI(FF), FL, ULSA and FFO require operating multiple spacecraft simultaneously
Pre-launch test complexity	H	M	M	M	M	M	• NI(M), LAC, FL, FFO require testing of large optical systems, with some active elements • NI(FF) requires testing of interactive systems separated by large distances

Ranking and Summary

TRW

Architecture	Rank	High Risks	Medium Risks	Low Risks
LAC	1	0	7	6
NI(M)	2	0	9	6
FL	4	0	10	8
FFO	3	0	10	6
NI(FF)	6	1	11	5
ULSA	5	0	12	4

- LAC, NI(M), ULSA, FFO, and FL all offer only moderate risks
- NI(FF) system testing is a potential high risk

Reliability/Robustness is Determined by Degree of Functional Redundancy

- Reliability is inversely proportional to system complexity
  - Measured as the quantity of functionally independent elements
- Robustness is graceful degradation
  - Functional redundancy enables a system to operate at an acceptable level in the face of single-point failures in the individual elements
  - Operational flexibility in the system is dependent on the distribution of function among the individual elements

Each Architecture Can Be Broken Into System Elements

TRW

Architecture	System Elements	Definition
NI(FF)	Collecting Optics	Collecting apertures including optics for transmitting beams to combiner
	Combining Instrument	Beam combiner including all pathlength control and internal metrology
	Formation Flying System	Includes all inter-spacecraft communication, ranging systems, and the needed control capability; each spacecraft hosts a node of the system
	Collector Spacecraft	Spacecraft that carries the starlight collecting optics, including all propulsion, thermal control, and pointing control
	Combiner Spacecraft	Spacecraft that carries the starlight combing instrument, including all propulsion, thermal control, and pointing control
NI(M)	Collecting Optics	Collecting apertures including optics for transmitting beams to combiner
	Combining Instrument	Beam combiner including all pathlength control and internal metrology
	Spacecraft	Spacecraft that carries the interferometer, including thermal control, deployment mechanisms, and pointing control
LAC	Telescope	Deployable telescope, including optical train wavefront control
	Instrument	Instrument package with focal planes, spectrometer equipment, and internal thermal control
	Spacecraft	Spacecraft that carries the telescope and instrument, including thermal control, and pointing control
FL	Collecting Optics	Fresnel lens, including any deployment mechanisms
	Eye Piece Telescope	Collecting telescope that gathers focused light from Fresnel lens, including the optical train and pointing control
	Instrument	Instrument package with focal planes, spectrometer equipment, and internal thermal control
	Formation Flying System	Includes all inter-spacecraft communication, ranging systems, and the needed control capability; each spacecraft hosts a node of the system
	Collector Spacecraft	Spacecraft that carries the Fresnel lens, including all propulsion, thermal control, and pointing control
	Eye Piece Spacecraft	Spacecraft that carries the eye piece telescope and instrument including all propulsion, thermal control. And pointing control

TRW

System Element Definition (Cont'd)

Architecture	System Elements	Definition
ULSA	Collecting Optics	Collecting mirror for the sparse aperture, including all figure control
	Eye Piece Telescope	Telescope that gathers focused light from sparse aperture, including the optical train and pointing control
	Instrument	Instrument package with focal planes, spectrometer equipment, and internal thermal control
	Formation Flying System	Includes all inter-spacecraft communication, ranging systems, and the needed control capability; each spacecraft hosts a node of the system
	Collector Spacecraft	Spacecraft that carries an individual aperture, including all propulsion, thermal control, and pointing control
	Controller Spacecraft	Spacecraft that carries the formation flying system
	Instrument Spacecraft	Spacecraft that carries the eye piece telescope and instrument including all propulsion, thermal control, and pointing control
FFO	Occulter	Occulting body, including all deployment mechanisms
	Telescope	Telescope that points at the occulter, including the optical train and pointing control
	Instrument	Instrument package with focal planes, spectrometer equipment, and internal thermal control
	Formation Flying System	Includes all inter-spacecraft communication, ranging systems, and the needed control capability; each spacecraft hosts a node of the system
	Occulter Spacecraft	Spacecraft that carries the occulter, including all propulsion, thermal control, and pointing control
	Telescope Spacecraft	Spacecraft that carries the telescope and instrument including all propulsion, thermal control, and pointing control

Elements Assessed for Impact Due to Loss or Degradation

TRW

Parameter	Definition
System Element	• The highest level of non-identical architecture component • Key instrument elements, especially those that would likely be manufactured as an integrated unit • Each type of spacecraft is a separate element category
Quantity	• Minimum number of each element needed for architecture
Loss of 1 Element End Mission	• If one of these elements is lost, is the mission unable to fulfill its objectives
Element Internally Redundant	• Can the element be made internally redundant to increase reliability • Instruments are not considered redundant, since multiple focal plane detectors or their equivalent are usually not flown • Telescopes are not considered to carry spare optics • Spacecraft are considered to be fully redundant internally
Compensate for Degradation in 1 Element	• Degradation includes damage to a portion of a mirror, loss of pixels in a focal plane, failure in one node of a formation flying system, reduction in spacecraft capabilities • Damage to on collector in a nulling interferometer impacts the entire instrument, while damage to the collector of an imaging system can be compensated • Restricting operations can compensate degradations in spacecraft systems • For ULSA, degradation in the formation flying system could be compensated by removing the faulty collecting spacecraft

Impact Assessments

Architecture	System Elements	Quantity	Loss of 1 Element End Mission	Element Internally Redundant	Compensate Degradation in 1 Element
NI(FF)	Collecting Optics	4+	YES	NO	NO
	Combining Instrument	1	YES	NO	NO
	Formation Flying System	1	YES	YES	NO
	Collector Spacecraft	4+	YES	YES	YES
	Combiner Spacecraft	1	YES	YES	YES
NI(M)	Collecting Optics	4+	YES	NO	NO
	Combining Instrument	1	YES	NO	NO
	Spacecraft	1	YES	YES	YES
LAC	Telescope	1	YES	NO	YES
	Instrument	1	YES	NO	YES
	Spacecraft	1	YES	YES	YES

TRW

Impact Assessments (Cont'd)

Architecture	System Elements	Quantity	Loss of 1 Element End Mission	Element Internally Redundant	Compensate Degradation in 1 Element
FL	Collecting Optics	1	YES	NO	YES
	Eye Piece Telescope	1	YES	NO	YES
	Instrument	1	YES	NO	YES
	Formation Flying System	1	YES	YES	NO
	Collector Spacecraft	1	YES	YES	YES
	Eye Piece Spacecraft	1	YES	YES	YES
ULSA	Collecting Optics	1	YES	NO	YES
	Eye Piece Telescope	1	YES	NO	YES
	Instrument	1	YES	NO	YES
	Formation Flying System	1	YES	YES	YES
	Collector Spacecraft	1	YES	YES	YES
	Controller Spacecraft	1	YES	YES	YES
	Instrument Spacecraft	1	YES	YES	YES
FFO	Occulter	5+	NO	NO	YES
	Telescope	1	YES	NO	YES
	Instrument	1	YES	NO	YES
	Formation Flying System	1	YES	YES	NO
	Occulter Spacecraft	5+	NO	YES	YES
	Telescope Spacecraft	1	YES	YES	YES

Reliability Risk Determined by Impact of Loss and Redundancy

- If loss of one element could end mission and it cannot be made internally redundant it has high reliability risk
- An element that cannot be lost, but can be made internally redundant has moderate reliability risk
- Elements that can be lost do not drive reliability risk

Rating of Architectures by Reliability Risk

TRW

Architecture	Rank	High Risks	Moderate Risks
LAC	1	2	1
ULSA	4	3	4
FL	3	3	3
FFO	2	2	2
NI(M)	5	5	1
NI(FF)	6	5	6

Reliability/robustness favors simple systems with minimum number of spacecraft and the ability to accept graceful degradation

Planet Imager and Life Finder are Third Generation of Origins Missions

- Planet Imager goal is to produce an image of an exo-Earth with a resolution of up to several hundred pixels across the planet diameter
- Life Finder is intended to produce high resolution spectroscopic analyses of an exo-Earth to determine the likelihood of biological processes

PI and LF Requirements Still in Development

TRW

Planet Imager	• Baselines of 5,000 (VIS) to 100,000 (IR) km • Collecting areas of 100 (IR) to 1,000 (VIS) km^2
Life Finder	• Spectral resolution of order R = 10,000

Phase 2 work will help define PI and LF requirements and the proper technology path for TPF technologies

Planet Imager is the Most Challenging System

- Baselines and collecting areas far beyond even TPF capabilities
  - Most likely architecture: free flying sparse aperture
  - Rotational synthesis imaging prohibited due to large baselines
- Long baselines not compatible with precision path length control
  - Will need direct detection of signal phase at each aperture and then combine signals digitally
    - VLBI technique
    - Optical amplification

Life Finder Angular Resolution Requirements Within TPF Ability

TRW

- LF only needs to be able to separate planetlight from starlight
- Collecting area needs increase to provide sufficient photons for high resolution spectroscopy

TPF Architectures Represent Different Approaches to Technology

TRW

Architecture	Technology Approach
Nulling Interferometer	• Adapt SIM technology to longer baselines and cryogenic systems • Insert nulling beam combiner technology • Develop either formation flying systems or large deployable structures
Large Aperture Coronagraph	• Adapt NGST technology to larger apertures • Insert precision coronagraph technology
Fresnel Lens	• Develop large Fresnel lens technology • Adapt NGST technology for downstream optics • Insert precision coronagraph technology
Free Flying Occulter	• Use NGST deployable optics technology • Adapt NGST optics to visible light • Adapt NGST large deployable sunshade technology to occulter • Develop high transmissivity material technology
Ultra Large Sparse Aperture	• Adapt NGST technology to large sparse apertures • Develop either formation flying systems or large structures assembled on orbit

Applicability of TPF Technology to Third Generation

TRW

Architecture	Technology		TPF		LF		PI
NI(FF)	Nulling beam combiner						
	Pathlength control						
	Formation flying						
NI(M)	Nulling beam combiner						
	Pathlength control						
	Large deployable structures						
LAC	Large deployable optics						
	Coronagraph						
FL	Large Fresnel optics						
	Coronagraph						
FFO	VIS NGST optics						
	Occulter technology						
ULSA	Large sparse apertures						
	On-orbit assembly						

Evolvability Assessment

TRW

- PI needs to put as much “glass” in space as possible
  – Practical limits of LAC and FL apertures may be reached at LF
- FL does not readily scale to larger systems due to high f/#
- Coronagraph and nulling techniques of no use to PI

ULSA is the Most Direct Path to Planet Imager

Architecture	Evolvability Ranking
ULSA	1
LAC	2
FL	2
NI(FF)	4
NI(M)	4
FFO	4

Legacy Conclusions

- Ultra Large Sparse Aperture is most direct path to PI
- All other concepts can lead to LF
- PI will still need to develop techniques for direct signal phase detection in the infrared to be practical

Costing Assumptions

- Used NGST and SIM elements (telescope, instrument, S/C, etc) times TPF complexity factor for basis of estimate
- Scaled up NGST and SIM element costs by other program costs (management, system engineering, ground element, I&T, etc)
- Where there are multiple units used a 60/40 NR/R split
- NGST Element Costs
  - S/C + Shade 300M
  - Instrument 350M
  - OTA 350M
- SIM Element Costs
  - Interferometer 525M
  - S/C + PSS 372M

Each Architecture Can Be Broken Into System Elements

TRW

Architecture	System Elements	Definition
NI(FF)	Collecting Optics	Collecting apertures including optics for transmitting beams to combiner
	Combining Instrument	Beam combiner including all pathlength control and internal metrology
	Formation Flying System	Includes all inter-spacecraft communication, ranging systems, and the needed control capability; each spacecraft hosts a node of the system
	Collector Spacecraft	Spacecraft that carries the starlight collecting optics, including all propulsion, thermal control, and pointing control
	Combiner Spacecraft	Spacecraft that carries the starlight combing instrument, including all propulsion, thermal control, and pointing control
NI(M)	Collecting Optics	Collecting apertures including optics for transmitting beams to combiner
	Combining Instrument	Beam combiner including all pathlength control and internal metrology
	Spacecraft	Spacecraft that carries the interferometer, including thermal control, deployment mechanisms, and pointing control
LAC	Telescope	Deployable telescope, including optical train wavefront control
	Instrument	Instrument package with focal planes, spectrometer equipment, and internal thermal control
	Spacecraft	Spacecraft that carries the telescope and instrument, including thermal control, and pointing control

System Element Definition (Cont'd)

Architecture	System Elements	Definition
FL	Collecting Optics	Fresnel lens, including any deployment mechanisms
	Eye Piece Telescope	Collecting telescope that gathers focused light from Fresnel lens, including the optical train and pointing control
	Instrument	Instrument package with focal planes, spectrometer equipment, and internal thermal control
	Formation Flying System	Includes all inter-spacecraft communication, ranging systems, and the needed control capability; each spacecraft hosts a node of the system
	Collector Spacecraft	Spacecraft that carries the Fresnel lens, including all propulsion, thermal control, and pointing control
	Eye Piece Spacecraft	Spacecraft that carries the eye piece telescope and instrument including all propulsion, thermal control, and pointing control
ULSA	Collecting Optics	Collecting mirror for the sparse aperture, including all figure control (primary only)
	Eye Piece Telescope	Telescope that gathers focused light from sparse aperture, including the optical train and pointing control
	Instrument	Instrument package with focal planes, spectrometer equipment, and internal thermal control
	Formation Flying System	Includes all inter-spacecraft communication, ranging systems, and the needed control capability; each spacecraft hosts a node of the system
	Collector Spacecraft	Spacecraft that carries an individual aperture, including all propulsion, thermal control, and pointing control
	Instrument Spacecraft	Spacecraft that carries the eye piece telescope and instrument including all propulsion, thermal control, and pointing control
FFO	Occulter	Occulting body, including all deployment mechanisms
	Telescope	Telescope that points at the occulter, including the optical train and pointing control
	Instrument	Instrument package with focal planes, spectrometer equipment, and internal thermal control
	Formation Flying System	Includes all inter-spacecraft communication, ranging systems, and the needed control capability; each spacecraft hosts a node of the system
	Occulter Spacecraft	Spacecraft that carries the occulter, including all propulsion, thermal control, and pointing control
	Telescope Spacecraft	Spacecraft that carries the telescope and instrument including all propulsion, thermal control, and pointing control

Cost Methodology

Architecture	System Elements	Quantity	Comparison Program Element	Complexity Factor
NI(FF)	Collecting Optics	4+	SIM Optics	1 x
	Combining Instrument	1	SIM Instrument	3 x
	Collector Spacecraft	4+	SIM Spacecraft Bus	0.9 x
	Combiner Spacecraft	1	SIM Spacecraft Bus	0.9 x
NI(M)	Collecting Optics	4+	SIM Optics	1 x
	Combining Instrument	1	SIM Instrument	3 x
	Spacecraft	1	SIM Spacecraft Bus + PSS	1.9 x
LAC	Telescope	1	NGST Telescope	4 x
	Instrument	1	NGST Instrument	1 x
	Spacecraft	1	NGST Spacecraft Bus	1.5 x

Cost Methodology (Cont'd)

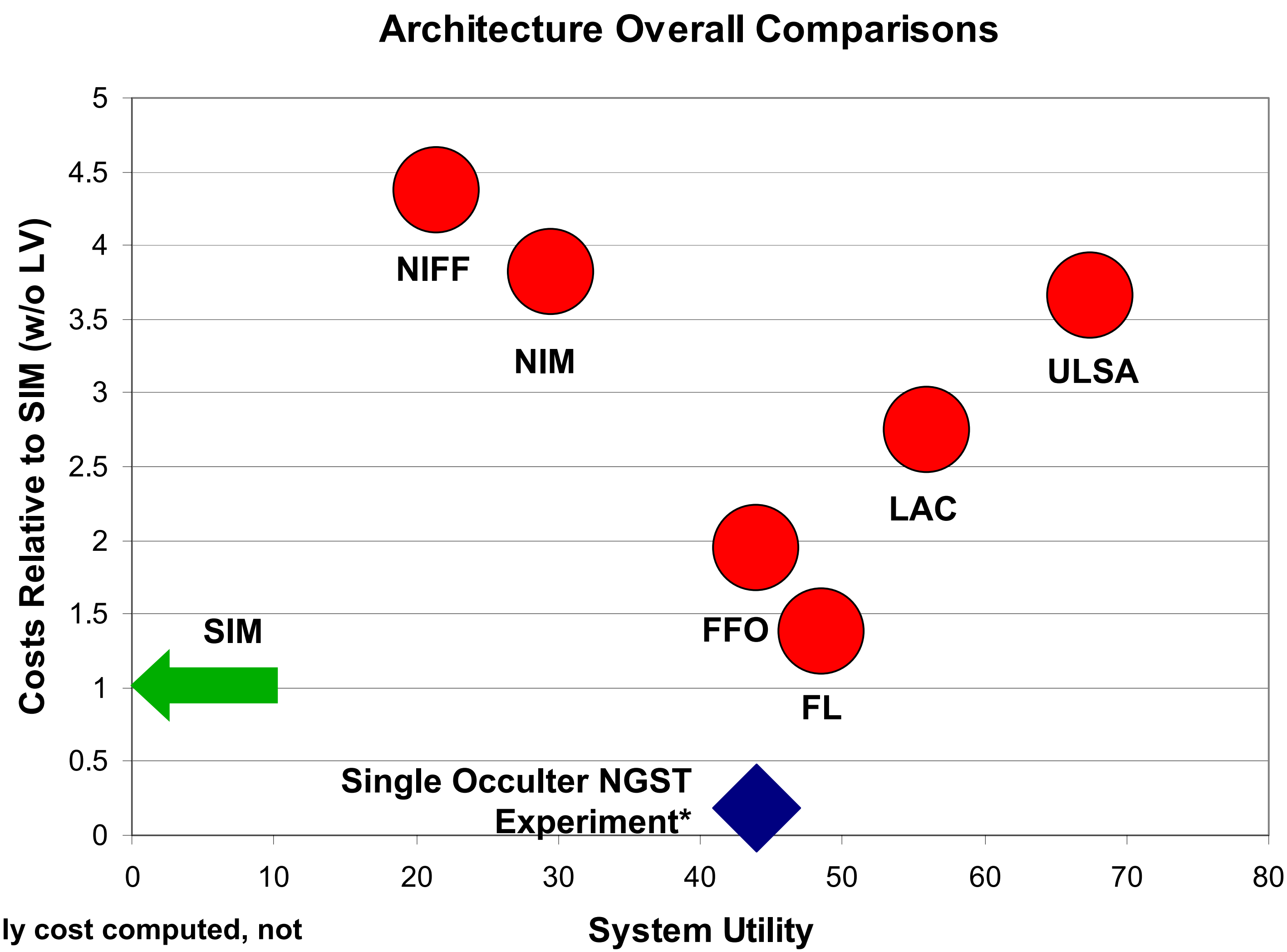
Architecture	System Elements	Quantity	Comparison Program Element	Complexity Factor
FL	Fresnel Lens	1	Engineering Estimate	1 x
	Eye Piece Telescope	1	NGST Telescope	0.5 x
	Instrument	1	NGST Instrument	1 x
	Collector Spacecraft	1	NGST Spacecraft Bus	0.5 x
	Eye Piece Spacecraft	1	NGST Spacecraft Bus	0.75 x
ULSA	Collecting Optics	1	NGST Optics	4 x
	Eye Piece Telescope	1	NGST Telescope	0.4 x
	Instrument	1	NGST Instrument	1.6 x
	Collector Spacecraft	1	NGST Spacecraft Bus	2 x
	Instrument Spacecraft	1	NGST Spacecraft Bus	0.75 x
FFO	Occulter	5+	Engineering Estimate	1 x
	Telescope	1	NGST Telescope	2 x
	Instrument	1	NGST Instrument	0.5 x
	Occulter Spacecraft	5+	NGST Spacecraft Bus	0.3 x
	Telescope Spacecraft	1	NGST Spacecraft Bus	1 x

Overall Assessment Rates System Utility Against Cost

- System utility involves a weighted ranking of science utility, technical risk, reliability risk, and legacy
- Points assigned for Highs (3), Mediums (2), and Lows (1)
- System Utility comprises 2/3 Science Utility, 2/9 Risk, 1/9 Legacy
  - System Utility = Science Utility + Legacy - (Technical Risk + Reliability Risk)

Small Direct Imagers Provide Optimal Utility/Dollar

TRW



*Only cost computed, not system utility