TRW Space & Electronics Group

Very Large Sparse Aperture Concept

Martin Flannery

Sparse Aperture Concept Description

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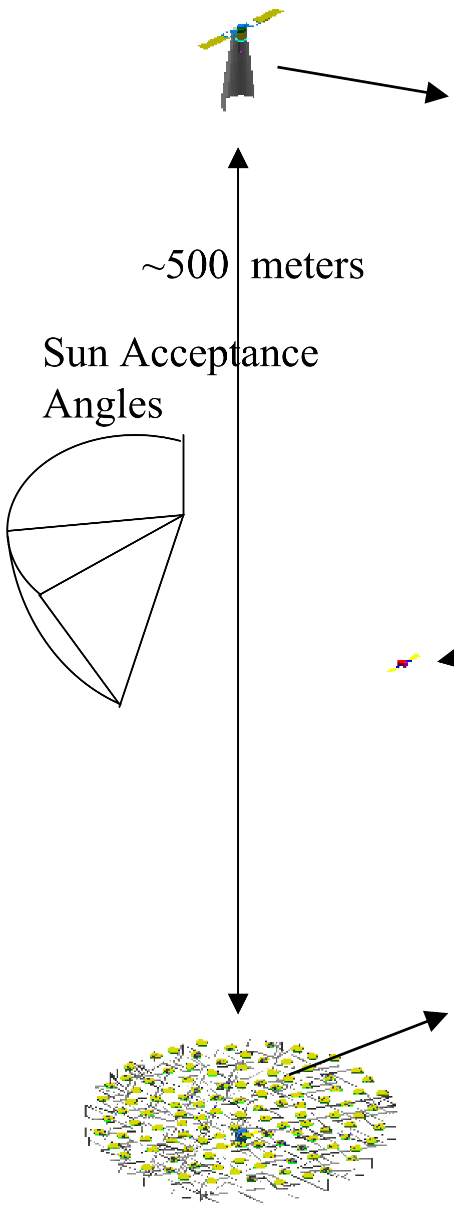
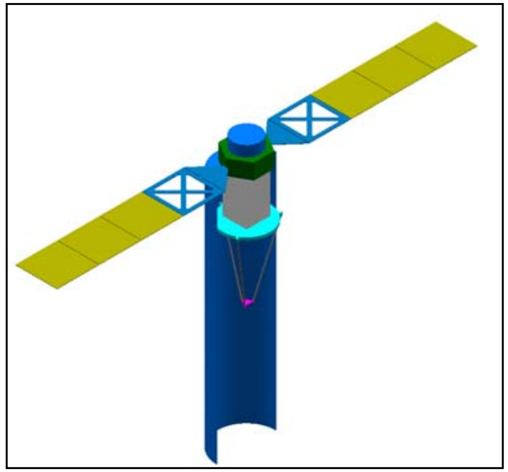


"Eyepiece" Spacecraft

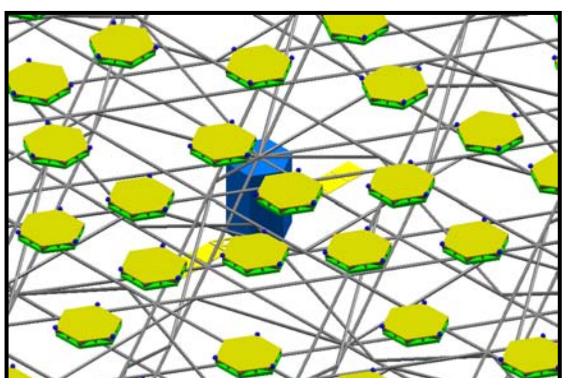


- Eyepiece spacecraft is self contained assembly housing secondary, additional optics, simple occulting spot and focal plane
- Sugar-scoop baffle provides sunlight rejection and optics cooling

Metrology/Navigation Spacecraft

- Metrology/Navigation spacecraft provides laser metrology between secondary spacecraft and the primary

Primary with Subapertures



- Primary is a lightweight monolithic truss supporting subapertures
- One satellite performs formation flying and actuators position of individual mirror elements

Concept Description

~120 4-meter subapertures sparsely filled (5-20%) 100-meter class giant telescope

- Operation in IR
- Excellent resolution
- Large collecting area

Primary mirror:

~100-m monolithic supporting structure

- Spherical mirrors with radius of curvature control
  - Simulates elements of a large parabola
  - Passively cooled mirrors (~100K) allows operation into LWIR
- Primary spacecraft formation flies to sub-centimeter accuracy

Eyepiece spacecraft directly images the exo-solar system

- 3-meter secondary, with tertiary and quaternary
- Simple occulting spot reduces starlight intensity
- 'Sugar-scoop' thermal baffling

Metrology/Navigation spacecraft measures and directs spacecraft and optics into position

- 3-color laser metrology measures optical elements to nanometer accuracy
- Directs spacecraft and optical elements into alignment

Terrestrial Planet Finder

Sparse Aperture Trade Space Considered

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Orbits
- Earth
- Drift-Away
- L2

Wavelengths
- Visible
- 1-5 µm
- 5-20 µm

Primary Size
- 50m
- 150m
- 500m
- 1000m

Number of Subapertures
- ~50
- ~100
- ~300

Primary Geometry
- Free Flying
- Monolithic Structure

Subaperture Diameter
- ~2m
- ~4m
- ~5+m

Subaperture Figure
- Spherical - fixed
- Spherical - adjustable Rc
- Spherical - dual-axis adjusted Rc
- Off-axis paraboloid

Optical Configuration
- Prime focus
- 3 mirror
- 4 mirror
- 5 mirror
- 6 mirror

Legend
- Rejected (red)
- Baseline (black)

Trade Space Considerations

- Orbit
  - Earth orbit: Not appropriate for tight Formation Flying (FF)
  - Drift-away: Good for FF; not suitable for multiple launches; cannot be replenished
  - L2: Satisfactory for FF; easy replenishment

- Wavelengths
  - Visible: Imposes tight constraints on pointing/alignment accuracy
  - 1-5 µm: Acceptable pointing requirements; poor planet-finding performance
  - 5-20 µm: Good performance, easier pointing/alignment requirements

Trade Space Considerations (Cont'd)

- Primary size
  - 50 m: Good resolution at ~1 μm
  - 150 m: Acceptable resolution at ~10 μm
  - 500 m: Good resolution at 10 μm (however, poor fill factor)
  - 1000 m: Poor fill factor
- Primary structure
  - Free Flying: Allows flexibility in aperture size/spacing; significant operation complexity; significant cost for multiple spacecraft; allows PSF artifact movement and removal by displacing subapertures.
  - Monolithic Structure: Very large size requires on-orbit assembly; aperture not adjustable; low thrust upper stage to L2; allows PSF artifact movement and removal by spinning primary.

Number of sub-apertures
  - ~50: Results in a very sparse array
  - ~100: Results in a reasonable fill factor
  - ~300: Too expensive

Trade Space Considerations (Cont'd)

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Subaperture diameter

- ~2 m: Relatively inexpensive, but wastes LV volume
- ~4 m: Largest size fitting in typical LV
- ~5+ m: Requires a deployable design; added cost, complexity

Subaperture figure

- Spherical, fixed R_C: Inexpensive to fabricate; results in large aberrations
- Spherical, adjustable R_c: Permits first-order correction to match local figure of parabola; allows subaperature placement anywhere in primary; simple mechanism
- Spherical, dual-axis adjustable R_c: Permits second-order matching of local parabolic figure; more complicated
- Off-axis parabola: Not needed because linear obscuration is only 3-4% which does not effect sparse-aperture PSF significantly

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Trade Space Considerations (Cont'd)

- Optical configurations
  - Prime Focus
    - Poor fit to pixel size and PSF sampling unless system is quite long (f/30)
    - No field or Lyot stops
  - 3-mirror telescope:
    - Poor satellite/optical architecture unless a large convex secondary is used
    - Usually no field or Lyot stops
    - Poor fit to pixel size and PSF sampling
  - 4-mirror telescope:
    - Practical mechanical architecture with fewest mirrors
    - Concave secondary
    - Field and Lyot stops
    - Easy matching to pixel size and PSF sampling
  - 6-mirror telescope:
    - 3-mirror objective with 3-mirror off-axis reimaging anastigmatic
    - Concave secondary
    - Accessible intermediate field and Lyot stops for aberration correction and scattered-light control

System Sizing for Science

Science Driver	System Sizing for Science	Engineering Constraints
• Good imaging performance	• Fill factor for good imaging – >20% desired – <5% is poor	• < 50% for collision avoidance
	• Random positioning of sub-apertures to reduce structure/aliasing in PSF	–
	• Many subapertures	• ~ 100-150 subapertures; cost constrained
• Resolution to separate planet from star	• Planet-finding region substantially far from central spike (~10x)	–
	– 1 μm >30-m primary	• Collision concern at < 50 m for FF option
	– 10 μm >300-m primary	• Poor fill factor at > 150 m

Numerical Integration Produces Sparse Aperture PSF

TPF Terrestrial Planet Finder

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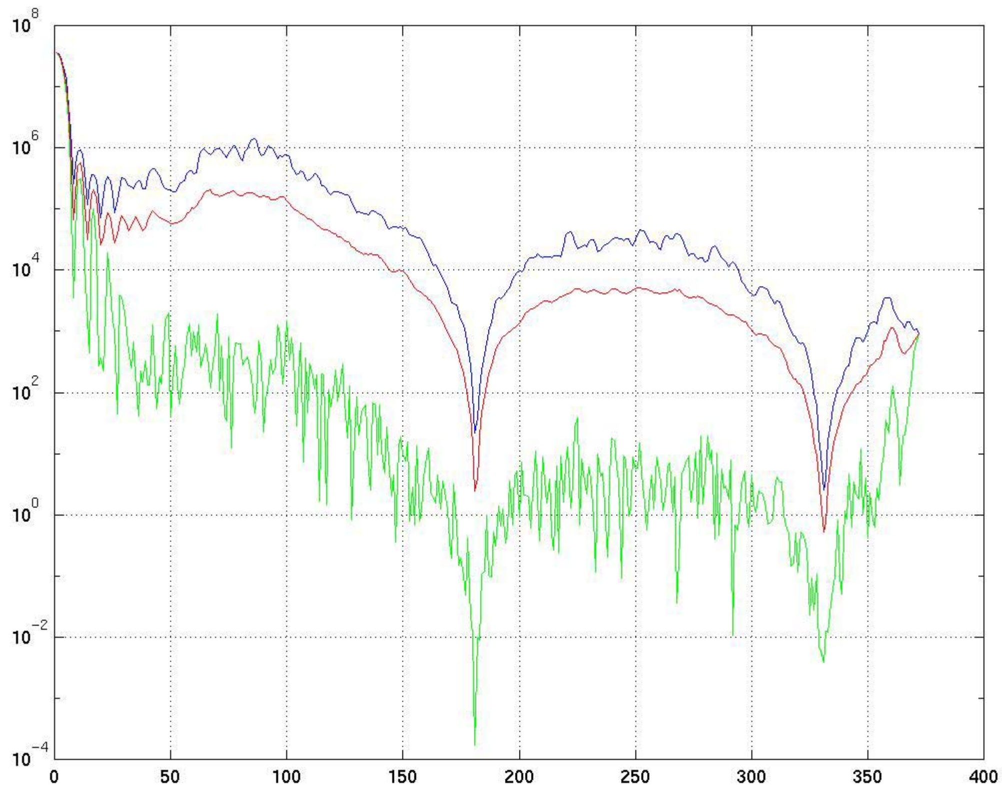
- Diffraction integral over complex aperture function adds subaperture Airy spots in phase with appropriate subaperture spacing
- 100 m primary mirror
- 120 x 4 m subapertures (19% fill factor)



- **Blue Curve: Maximum PSF**
- **Green Curve: Minimum PSF**
- **Red Curve: Average PSF**

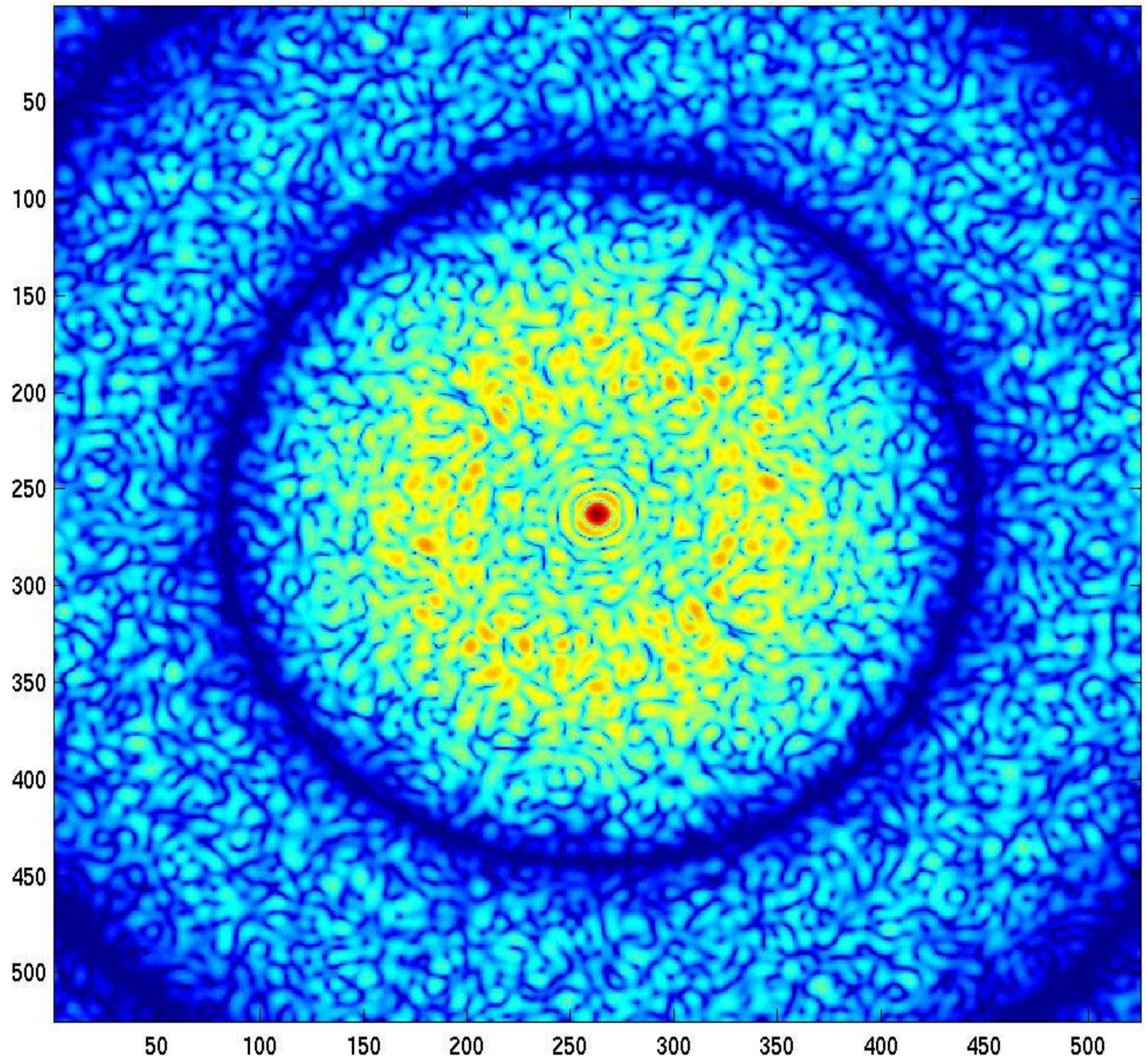
- **Axes are shown in pixel numbers.**

- **First Airy Ring of 120-m Aperture = 179 pixels = 0.0629 arcsec @ 1 μm = 0.629 arcsec @ 10 μm**

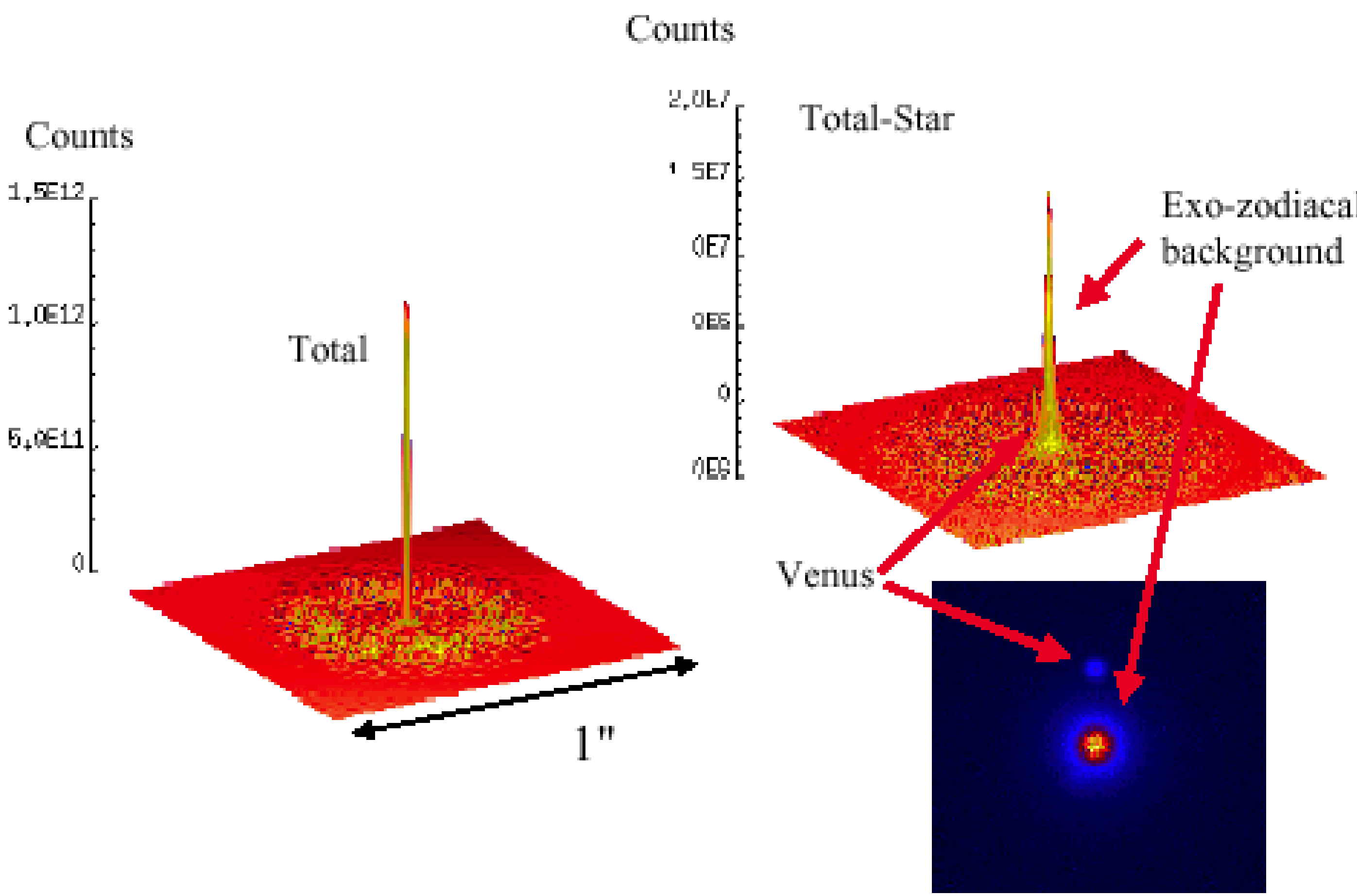
Sparse PSF

- Axes are shown in pixel numbers.

- First Airy Ring of 120-m Aperture
= 179 pixels
= 0.0629 arcsec @ 1 μm
= 0.629 arcsec @ 10 μm



Simulated Sparse Aperture Scene



Scene With Venus

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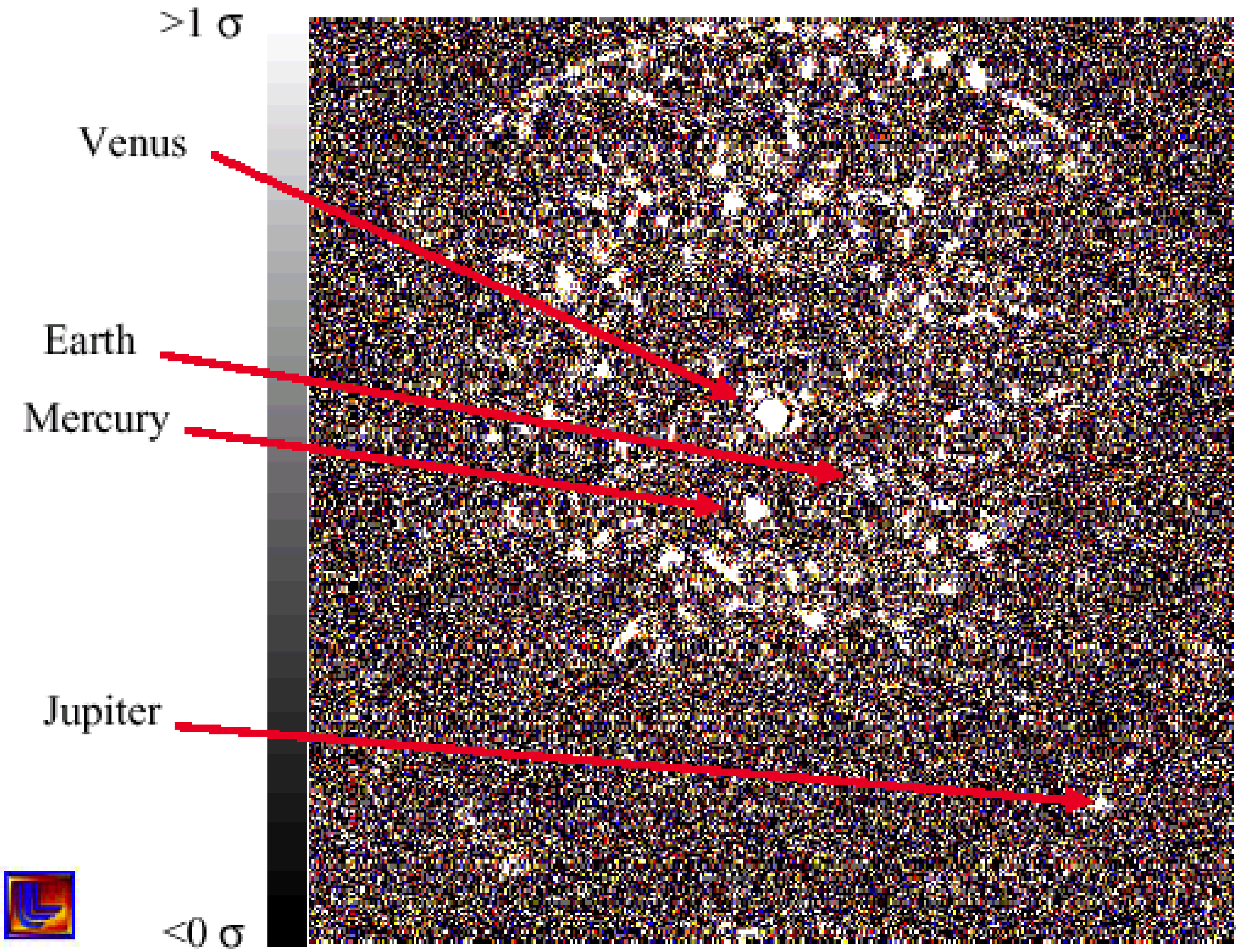
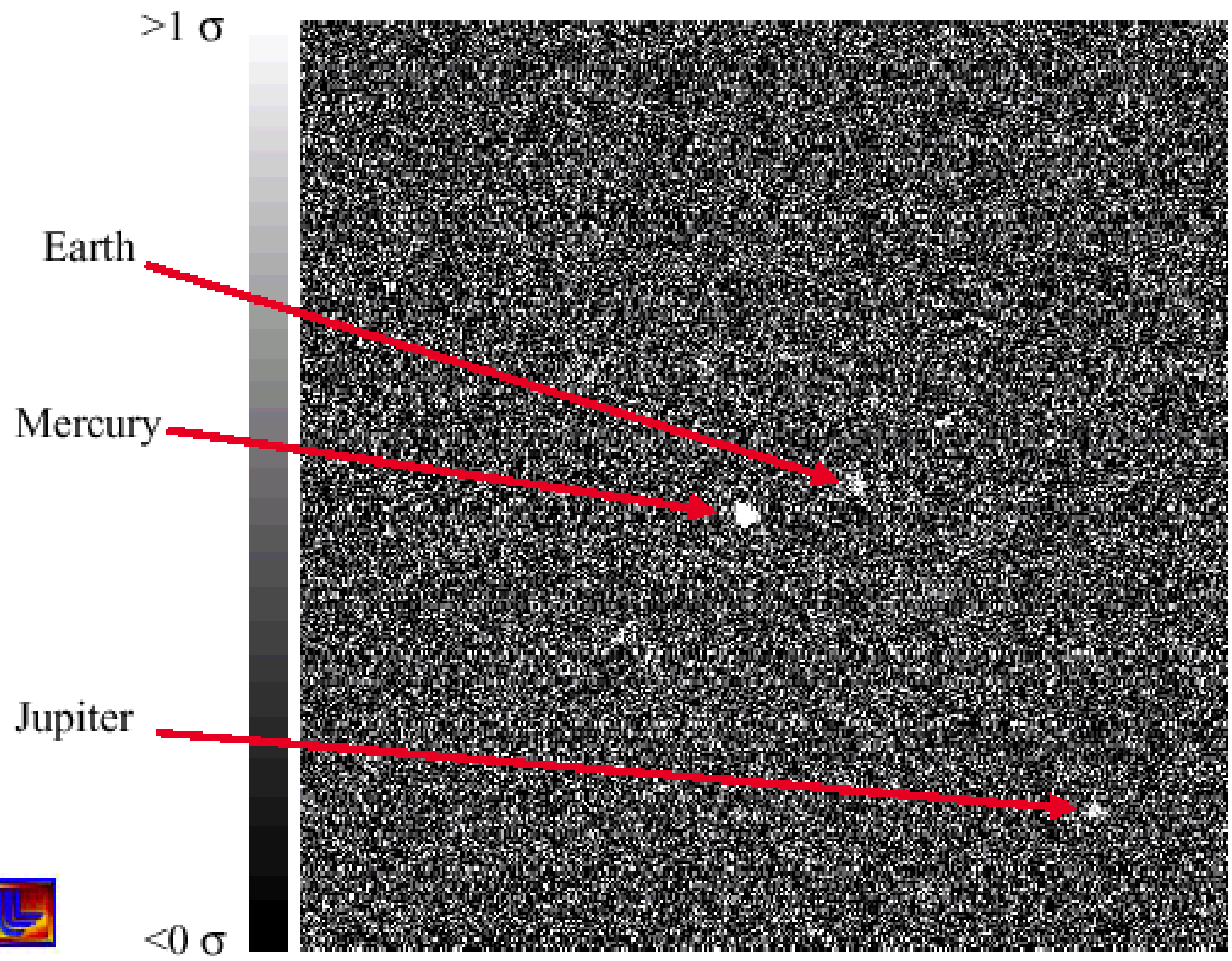


Scene Without Venus



Sparse Aperture Detection/ Characterization Times

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- Sun at 10 pc, Earth 0.1 arcsec from Sun; albedo = 0.38; 50% phase
- 100 m f/5 primary; 120 4-m subapertures randomly distributed
- 120K Mirror temperature
- SNR = 5

R ($\lambda/\Delta\lambda$)	Time (hours)				
	0.8 μm	1.0 μm	1.5 μm	8 μm	15 μm
2	1396	1333	1609	-	-
3	2066	2000	2469	2.3*	0.4
10	-	-	-	7.1	1.2
30	-	-	-	21.2	3.6
100	-	-	-	70.5	12.1
300	-	-	-	211.5	36.2
1000	-	-	-	704.9	120.7

* Charlie Bennett's model calculates 0.6-2.5 hours depending on assumptions (see backup charts)

Sparse Aperture Functional Block Diagram

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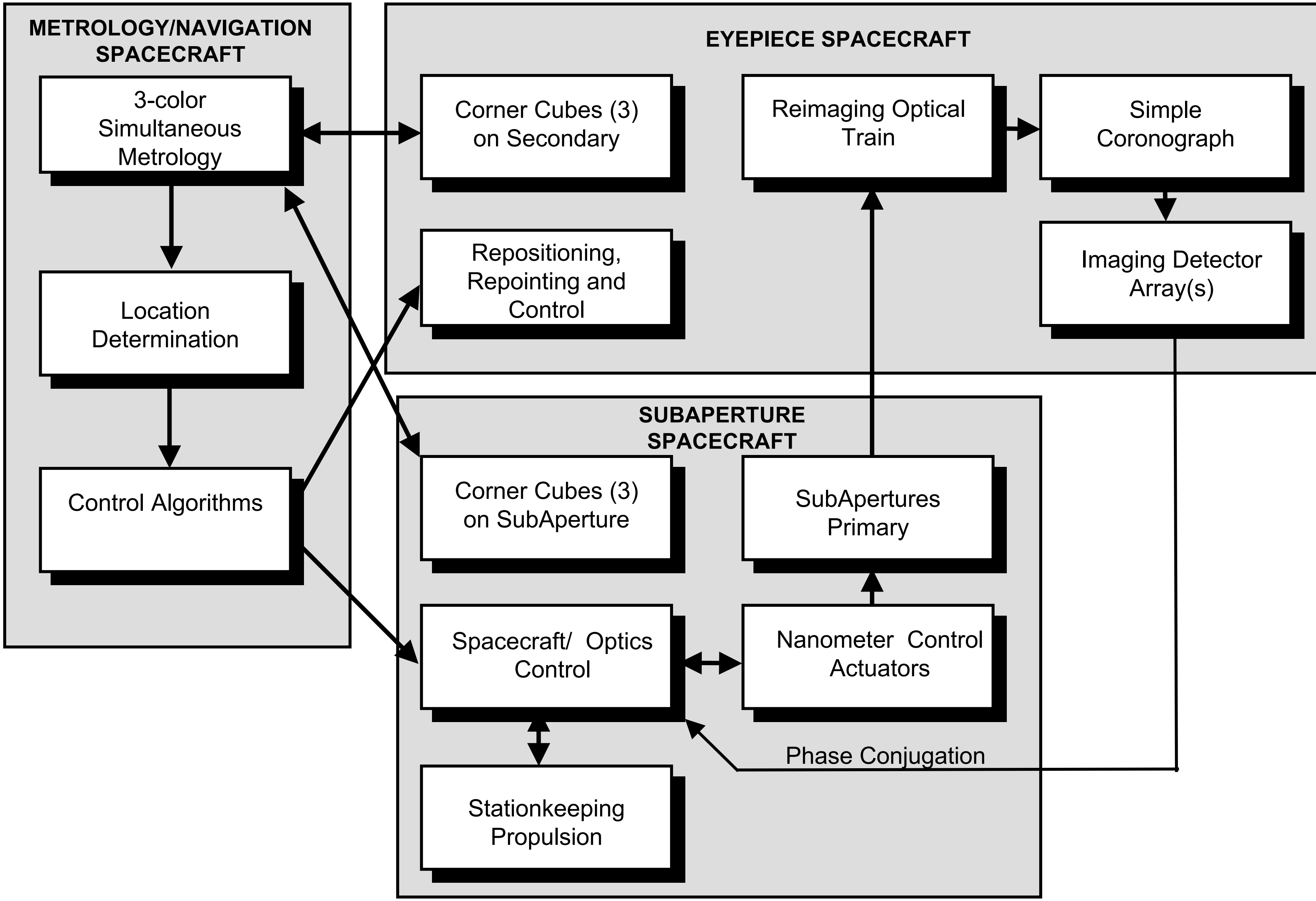

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Key Engineering Parameters

Engineering Parameter	Rationale
Formation Flying subaperture option	Allows primary reconfiguration to different diameters, subaperture arrangements
Monolithic supporting-structure before assembly and final orbit	Lower cost & risk than FF; launch subapertures into final orbit efficiently into orbit injection.
4-m collecting subapertures	Fits in existing LV fairings
120 subapertures	Provides good PSF
Spherical mirrors	Inexpensive to make
25 nm rms subaperture piston position accuracy	Can closely match appropriate parabola
16 nm rms subaperture tilt about center	Tilt less than half the primary Airy radius
1 nm metrology accuracy	
f/5 primary	Relieves alignment requirements
~100 K mirror temperatures	Easily achieved via passive cooling
	Enables operation into MWIR (<10 μm)
~1 cm spacecraft Formation Flying (FF) accuracy	Capability to be verified by ST-3
1 cm - 1 nm actuators	Bridges FF and optical control capabilities

Preliminary Optical Prescription of Telescope

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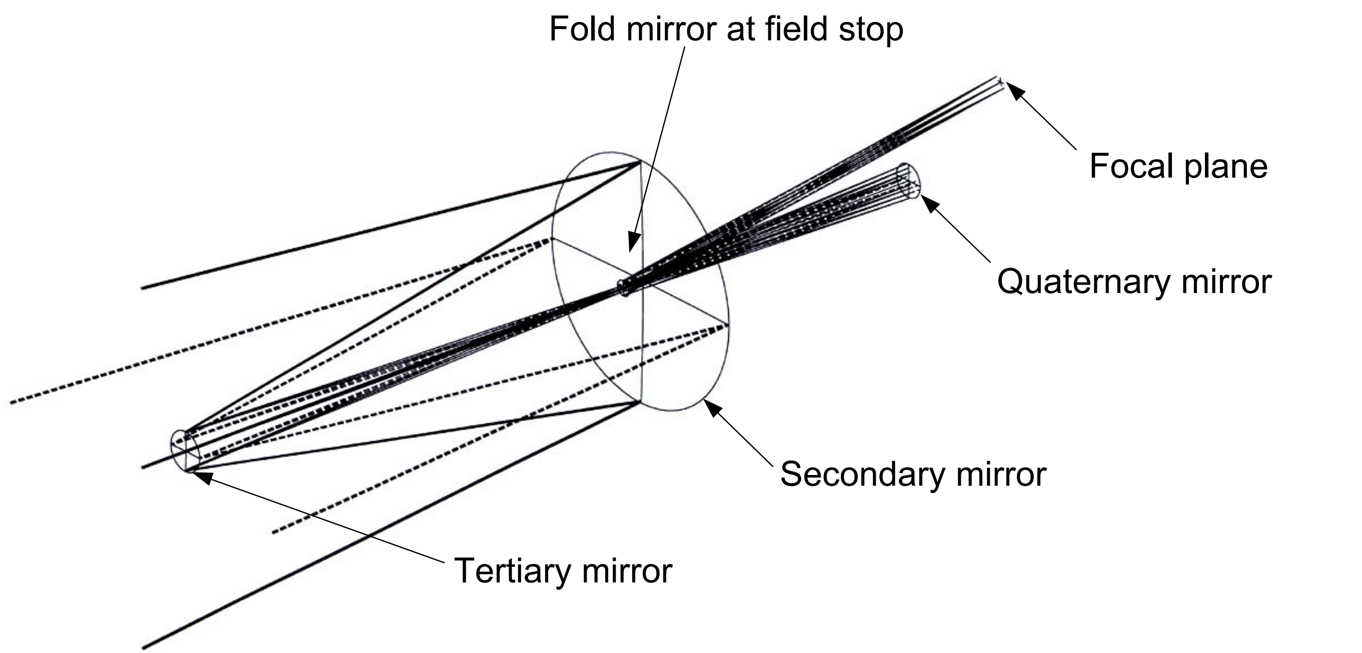
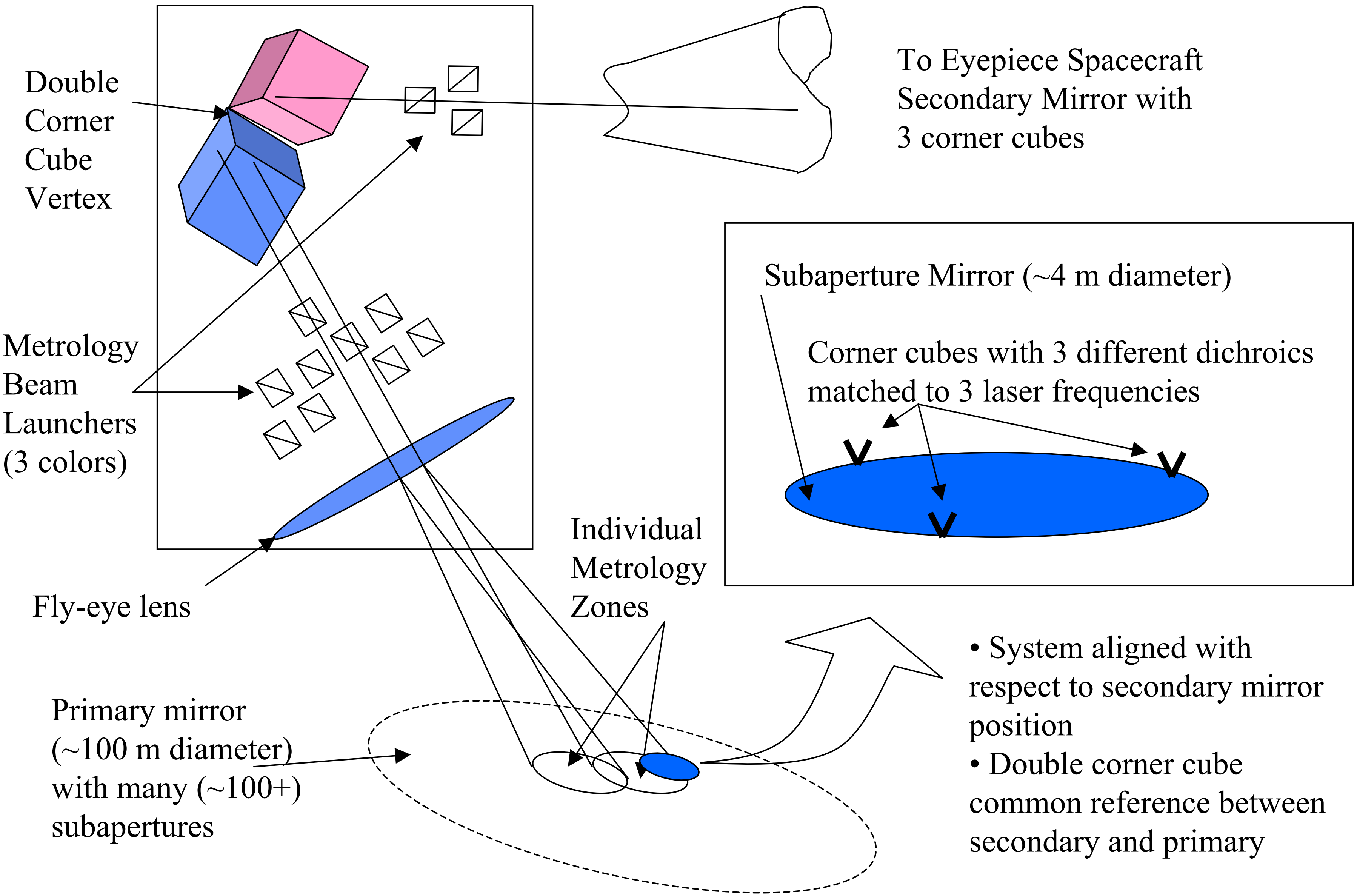
Optic	Diameter	Curvature Radii	Shape	Figure
Sparse Primary	< 125 m	1250 m	Concave	Parabola
Secondary	3.0155 m	22.0 m	Concave	Hyperboloid
Tertiary	0.423 m	2.11 m	Convex	Hyperboloid
Quaternary	0.300 m	4.70 m	Concave	Prolate Ellipsoid

FPA Characteristics: (5 arcsec FOV)

– 3726 x 3726 pixels, 40 μm (149 x 149 mm array)



Strawman Metrology System



- System aligned with respect to secondary mirror position
- Double corner cube common reference between secondary and primary

Technology Status

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Key Enabling Technology	Technology Status
Nanometer resolution metrology	Existing technology developed on SIM program
Nanometer metrology providing absolute distances over meter class zones	Absolute multi-wavelength interferometry done with capture ranges of ~10 m and accuracies of 0.1 - 1.0 μm
Simultaneous multi-color metrology	New development
Nanometer control over ~cm stroke	NGST actuators and SIM delay lines meet these requirements
100 m sparsely filled primary	Similar to Space Station dimensions; on-orbit construction may be common by TPF timeframe
Formation Flying Technology to <1 cm accuracy	In development on ST-3
4 meter variable curvature spherical mirrors, lightweight, inexpensive	AMSD and Kodak technology shows this is feasible
Passive thermal cooling of optics	Existing SIRTF technology; NGST developing similar technology

Tall Tent Poles

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- Multicolor metrology capable of nanometer resolution and absolute distance measurements over 100s meters
  - SIM has developed nanometer resolution metrology
  - Development of multicolor capability and absolute measurement is challenging
- Precision control of hundreds of optical elements to nanometers