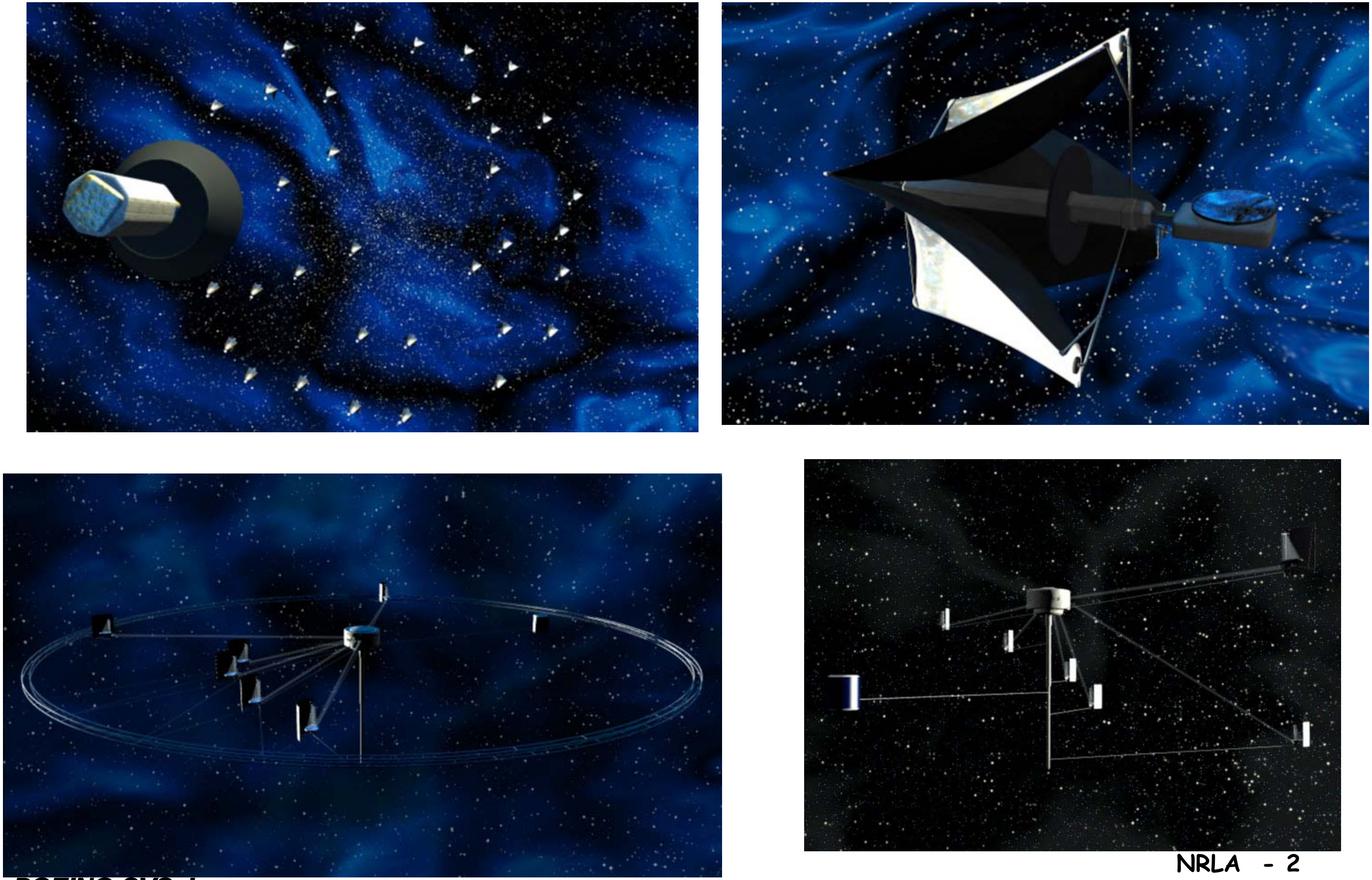
NRLA
Non-Redundant Linear Array

Hypertelescopes – A Refresher

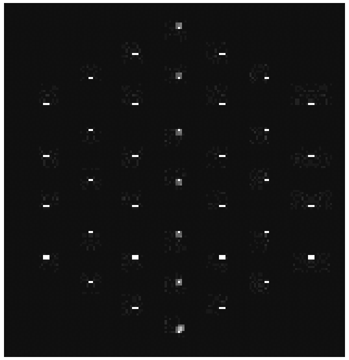


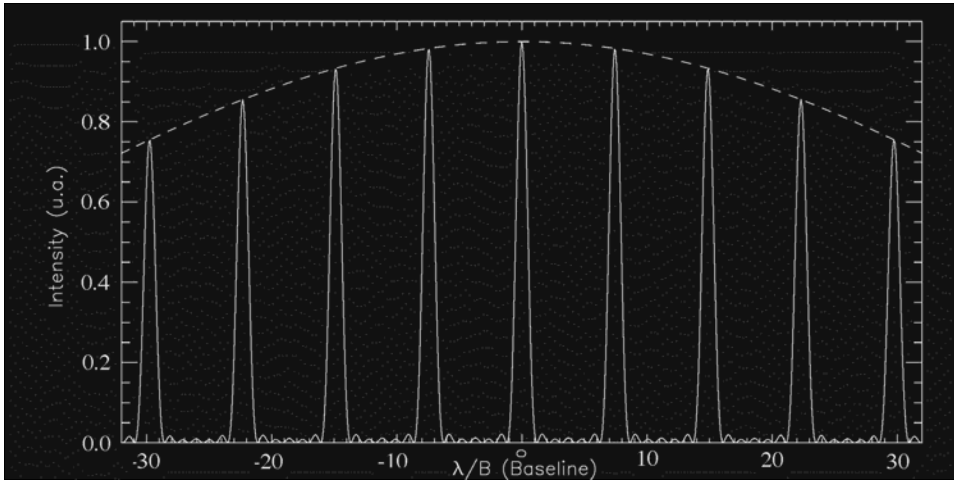
What is Pupil Densification?

- The light beams from a telescope array may be combined to form a real image.
- In order to form a stigmatic image, the beam arrangement must be a scaled map of the telescope arrangement (the Golden Rule).
- This requirement may be violated, forming a densified pupil.
- The densified pupil has, in general, complex characteristics, including translation-variant PSF and aliasing of sources outside a small FOV.
- For the special case of an on-axis quasi-point source, the densified pupil forms a compact, high-Strehl image.
- This image is suitable for coronagraphic nulling.

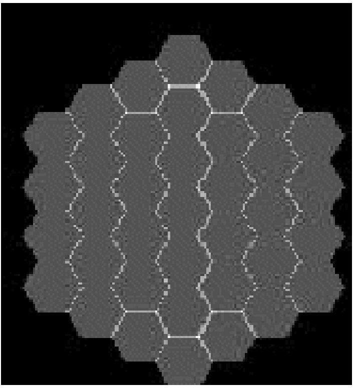
Pupil Densifier: Principle

Diluted Pupil



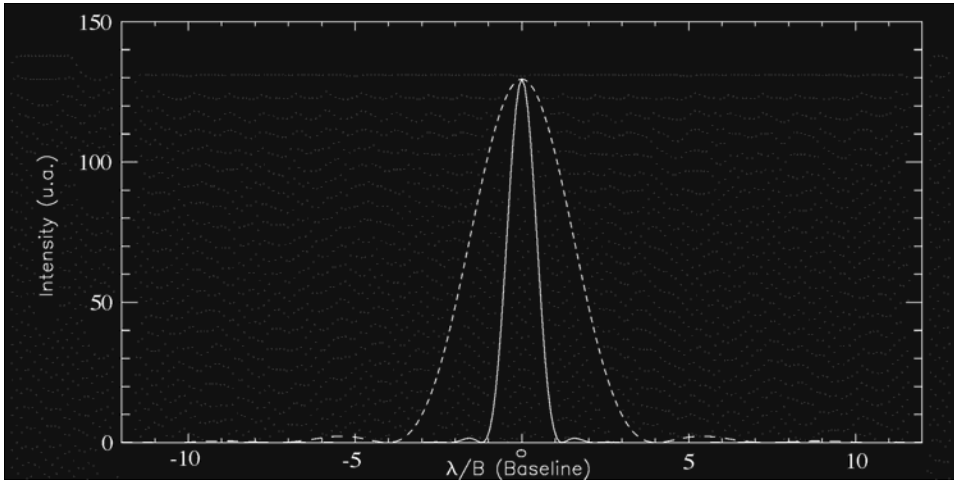


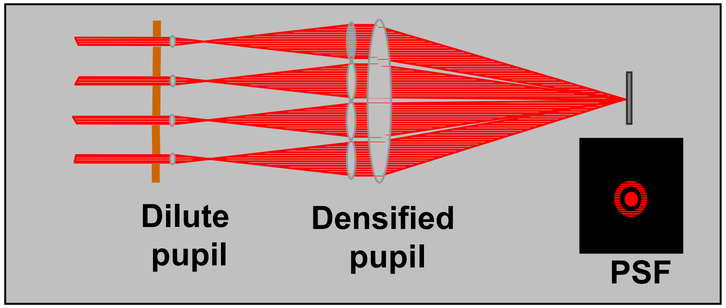
Densified Pupil



Central peak intensification

Field reduction

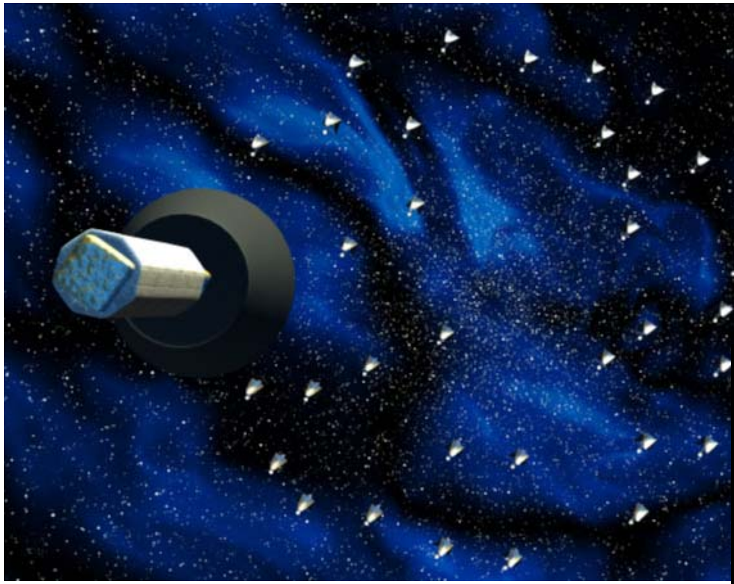




Not at same scale

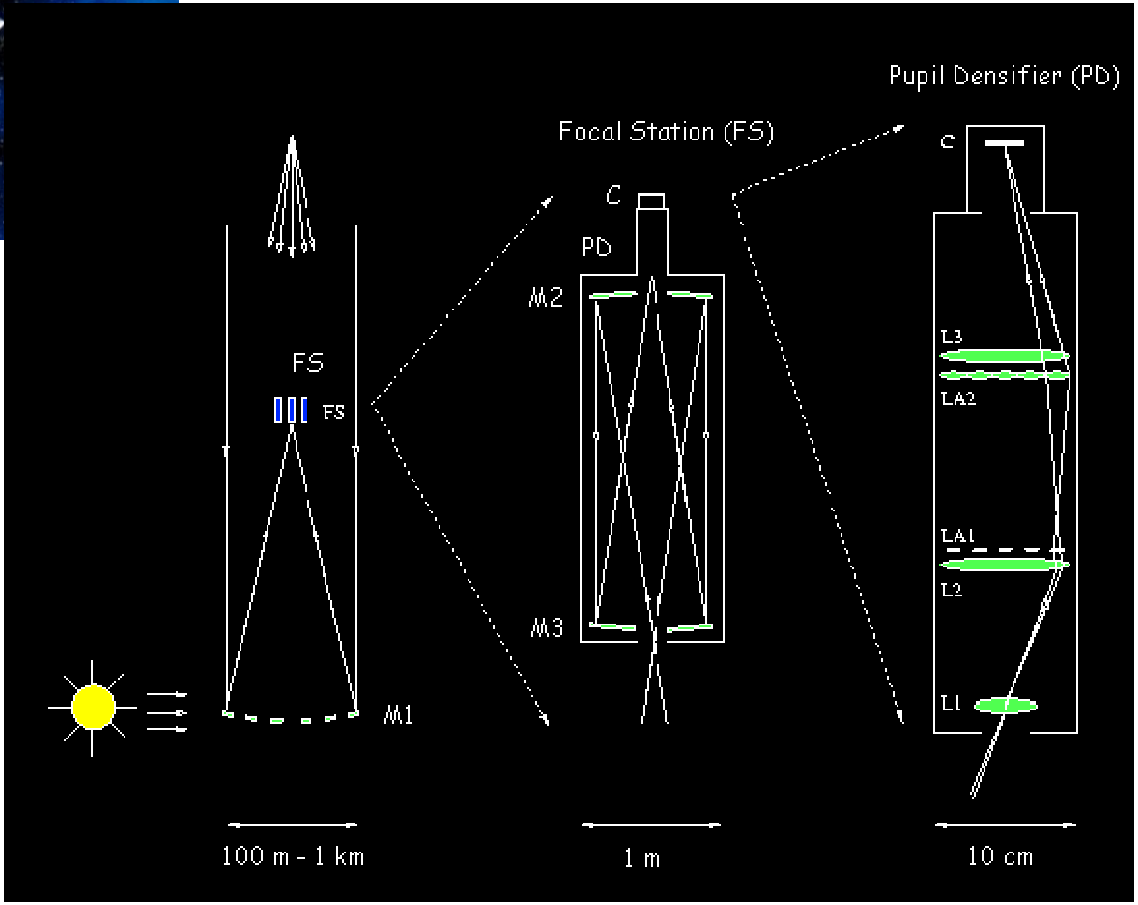
- *Image is intensified with respect to Fizeau array*
- *Direct imaging becomes possible*

Snapshot Imaging Array

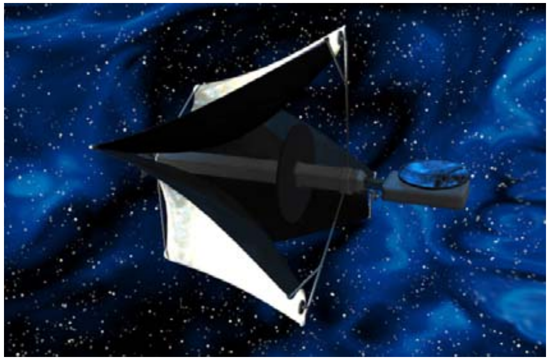


Array shown from focal station

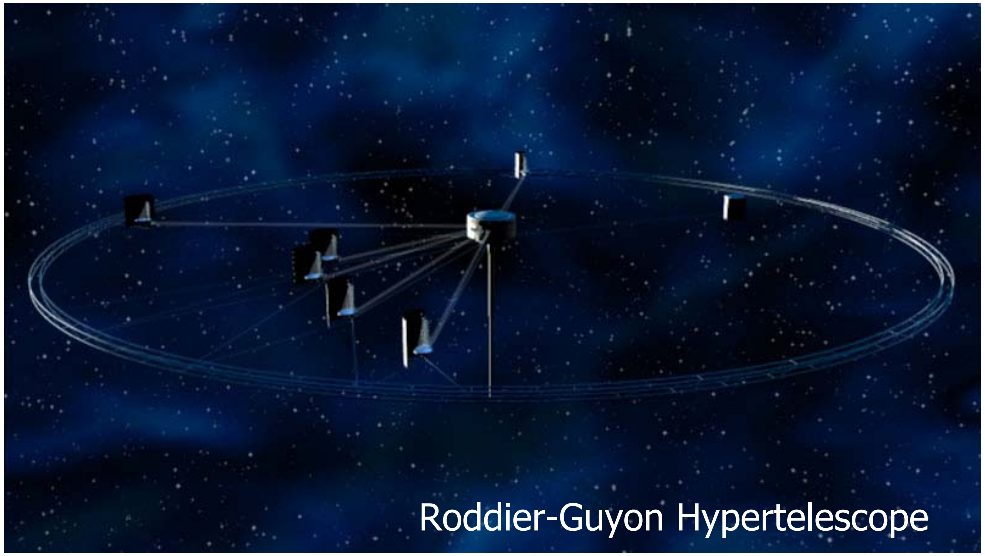
Plan view of array components



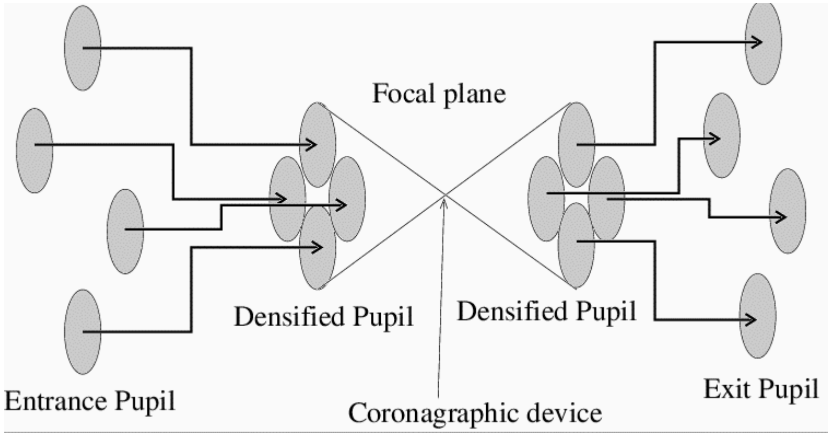
Free-flyer spherical mirror element



Evolution of Hypertelescopes to NRLA

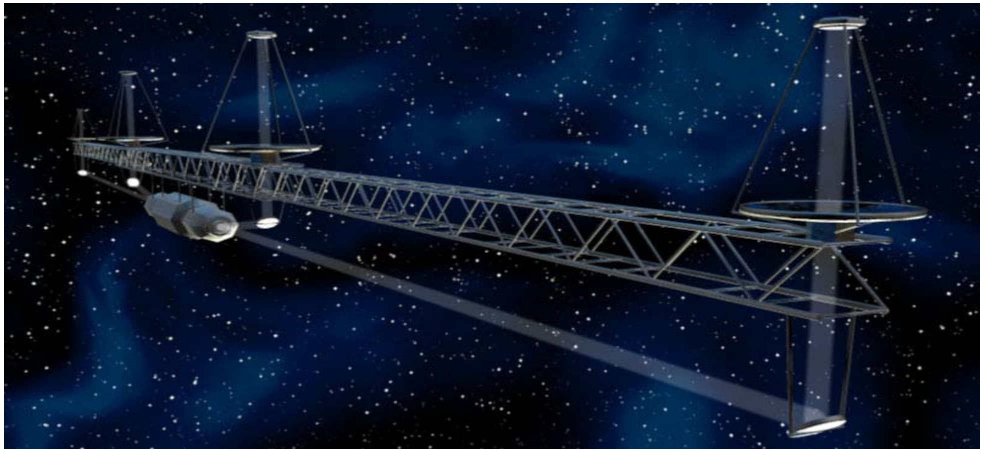


Pupil densification for the nulling coronagraph followed by pupil dedensification allows a simple and efficient nulling as well as a large field of view.



Array rotates about LOS to synthesize image after dedensification of pupil

Configure as a linear array; non-redundant spacing

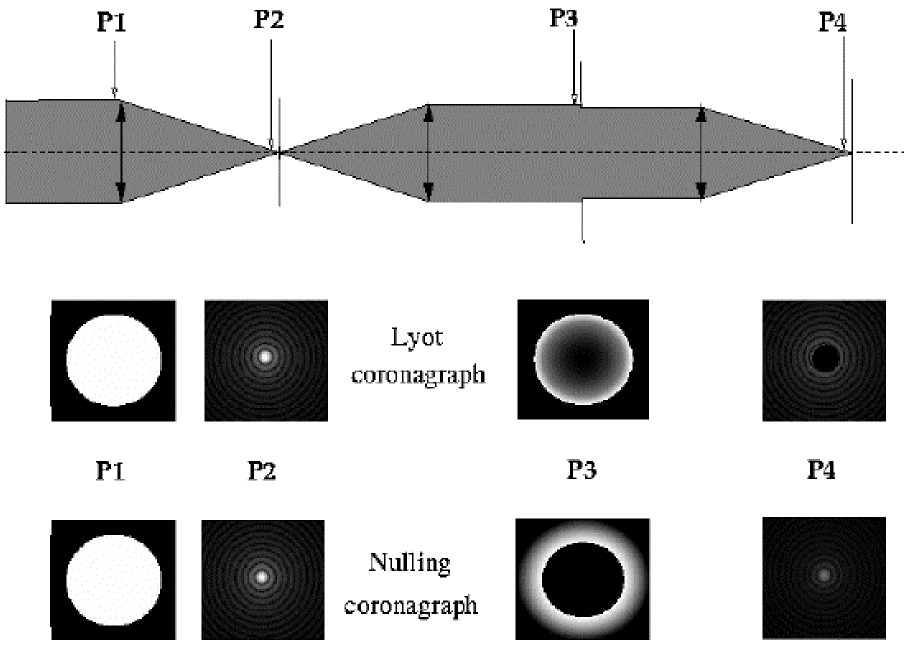


NRLA

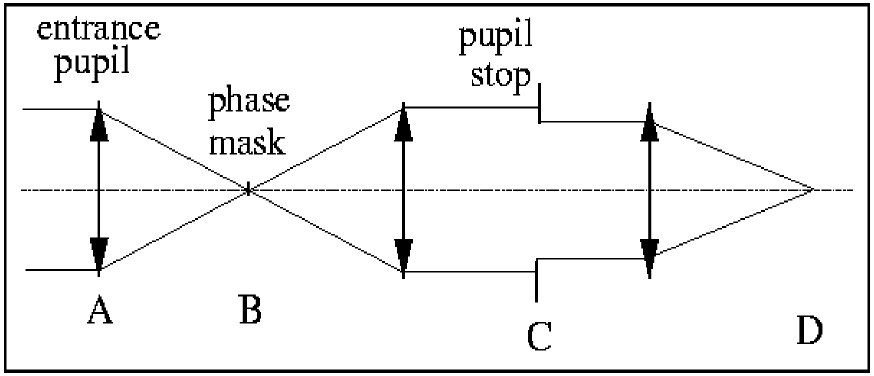
The Non-Redundant Linear Array (NRLA)

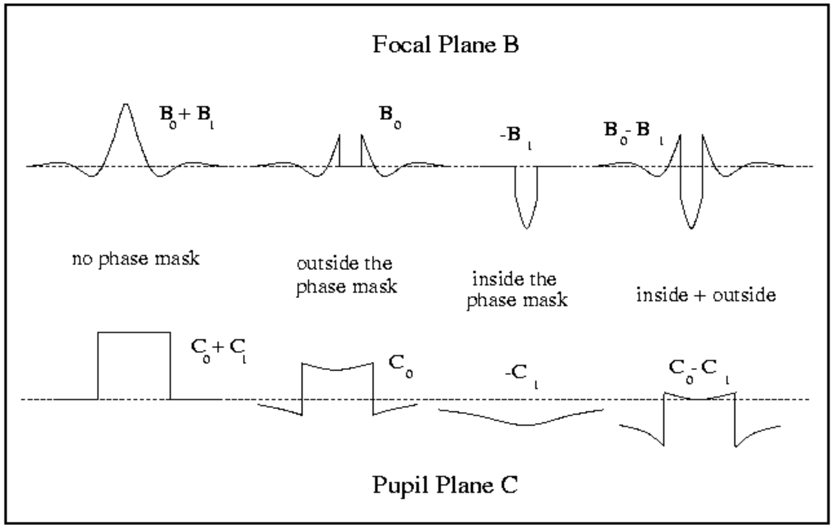
- The NRLA employs pupil densification to form a compact, real image of the star
- Coronagraphic nulling removes most of the stellar photons
- Pupil expansion and re-imaging provides the image Fourier components with full 1-d UV coverage along any single position angle from a single snapshot image
- Additional snapshot images during rotation by 180 degrees provide full 2-d UV coverage
- De-rotation of the snapshot images provides the residual stellar light map
- Inversion of the Fourier components yields the image

Imaging Coronagraphy with the Phase Mask Nulling Coronagraph



- The phase mask shifts the phase of the light by half a period
- The phase mask diameter is only 43% the diameter of the first dark Airy ring
- Thanks to an apodization mask in the pupil (densified pupil), the extinction is total for an on-axis point source
- This technique works with single and multiple pupils
- Ref. Roddier & Roddier, *PASP* 109:815-820 (July 1997)





- **This coronagraphic technique has been successfully tested in a laboratory.**

Pupil Densification in the NRLA

- The NRLA has a linear, non-redundant telescope arrangement.
- The linear pupil has been rearranged into a densified circle- YES!!!!, the linear array is mapped to a circular array
- The resulting wavefront is perfectly flat for an on-axis point source
- For near-axis sources, the wavefront is aberrated slightly - this effect is calculated in our simulations
- After the coronagraph, we re-expand the pupil. This removes the densified pupil aberrations of the off-axis sources.
- We form a new image on an array detector. This is a stigmatic image showing the exo-planet, including residual stellar leakage as re-imaged through the expanded pupil
- The leakage, determined from the registered sum of all snapshot images, is subtracted from each snapshot image

Fourier Sampling in the NRLA

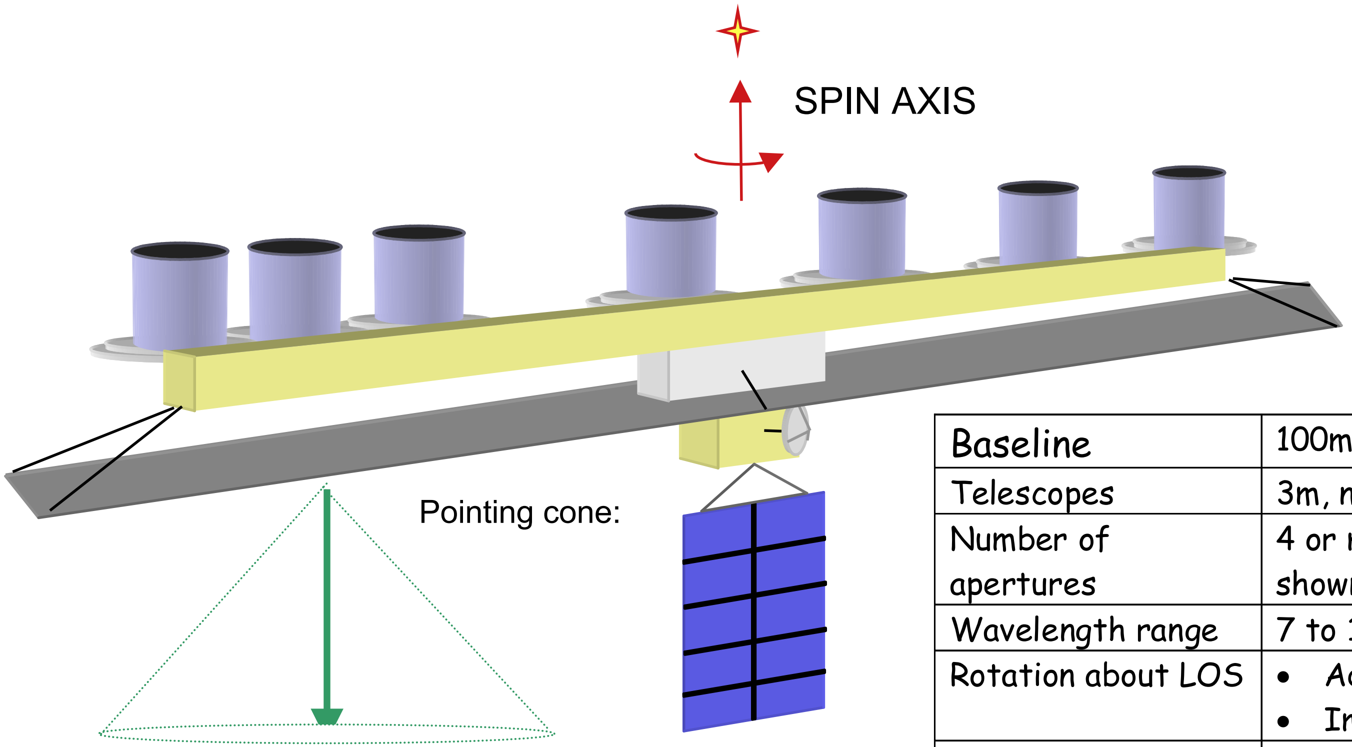
- The frequency content of each snapshot image is found by Fourier analysis
- The Fourier domain of the NRLA is known precisely. Most of the star leakage power is outside this domain, and can be ignored.
- Only the Fourier components in valid regions are retained.
- The rotational series of snapshots gives complete UV coverage
- Fourier inversion by standard techniques produces an image.
- Final noise level is set by photon noise of a fraction of the stellar leakage

Heritage of the Hypertelescope and NRLA

- Past and continuing
  - Image synthesis from Fourier components well developed in radio (for telescope arrays) and in infrared (aperture masking)
  - Optical interferometric beam combination experience - OPD control, phasing - ground based, JPL technology effort, SIM
  - Extensive hypertelescope design studies by several groups (OCA, OHP, UH). Lab demos (OHP)
  - Fizeau Interferometry Testbed - pupil densification demo - Goddard
- Future
  - NRLA is scalable to other 1-d and 2-d arrays; different telescope sizes, numbers, arrangements
  - Prepares technology path to free-flyer hypertelescope arrays
    - Only a free-flying, imaging array can respond to the long-range Navigator need for a Planet Imager

1.5.2 Complete end-to-end optical layout

- NRLA Characteristics:

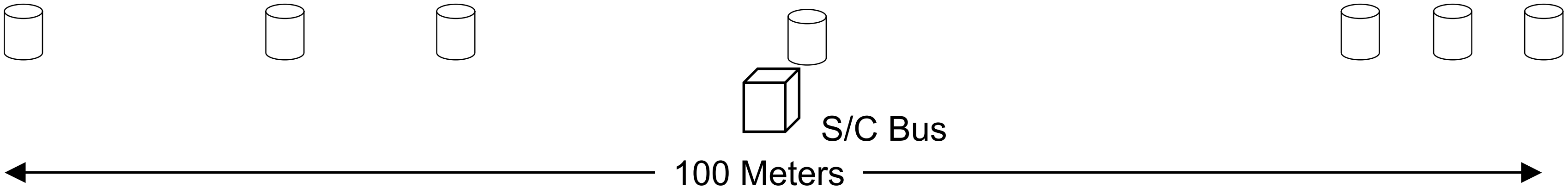


Nominal vector to sun when array is oriented with truss tangential to heliocentric orbit circle.

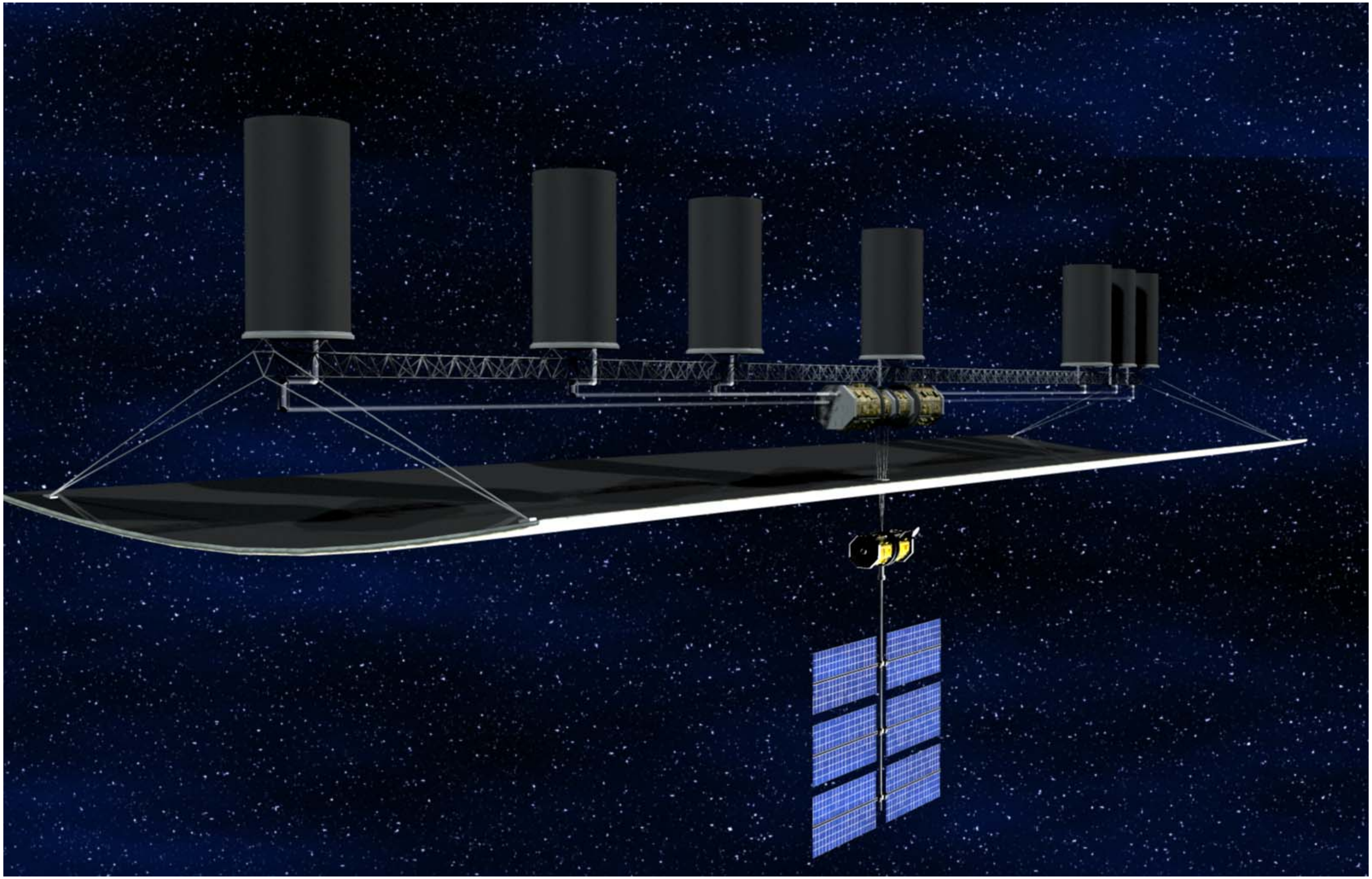
Baseline	100m
Telescopes	3m, non-redundant placement
Number of apertures	4 or more; point design for N=7 shown
Wavelength range	7 to 17 microns (7 to 20 possible)
Rotation about LOS	• Adjustable; nominal 5 hours • Image is formed in 1/2 rotation
Orbit	L2
Sun exclusion	45 degrees
Mass	9900 kg (3 launches)

1.5.1 Overall observatory geometry and array configuration

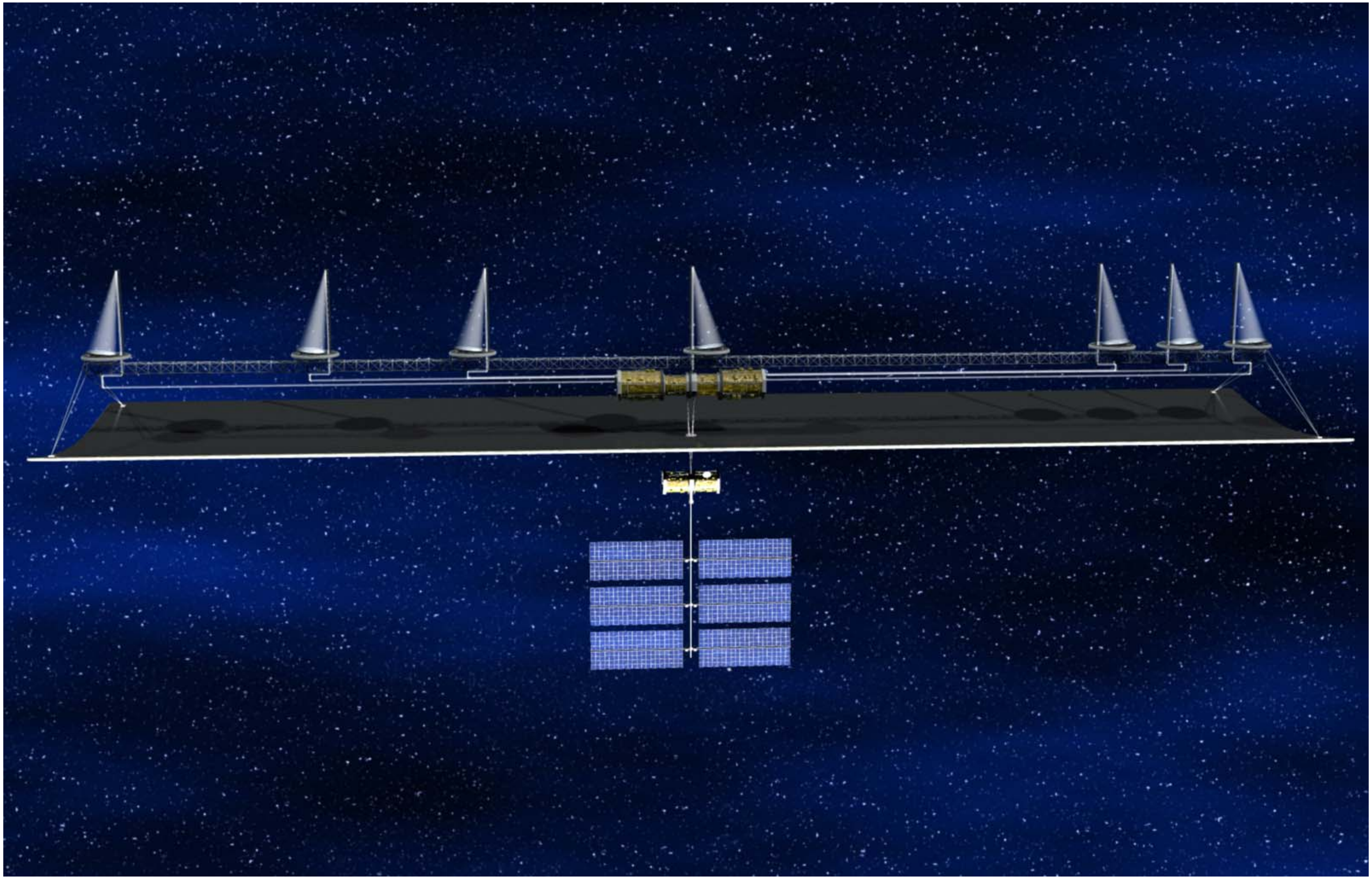
- A linear version of the Roddier/Guyon hypertelescope
  - Sparse array synthesis imager with embedded coronagraph
- Coronagraph (nulling phase mask or other) rejects on-axis starlight
  - Pupil densification used for efficient coronagraphy (redilution of beams after coronagraph)
- Truss-based structure, nonredundant placement of apertures
  - Needs coarse (static) delay lines to take up differential optical path lengths
  - Aperture placement optimized to maximize (u,v) coverage
- LOS Rotation: 2d image reconstructed from multiple snapshots after ½ rotation
- LOS rotation enables star residual suppression



Artist's rendering of NRLA



Artist's rendering of NRLA



NRLA - Self Assessment (1)

- Performance relative to the planetary detection science requirements
  - NRLA meets all draft TPF planet detection requirements
- Additional astrophysical science opportunities
  - NRLA is an imaging system with high potential for astrophysics
- Technology requirements and their feasibility in the mission time frame
  - Identified technology developments required, and those planned for other programs that NRLA must use to advantage; some technology development is required
- Life-cycle cost
  - NRLA cost estimate: $3B using full-cost accounting for STS flights

Self-assessment (2)

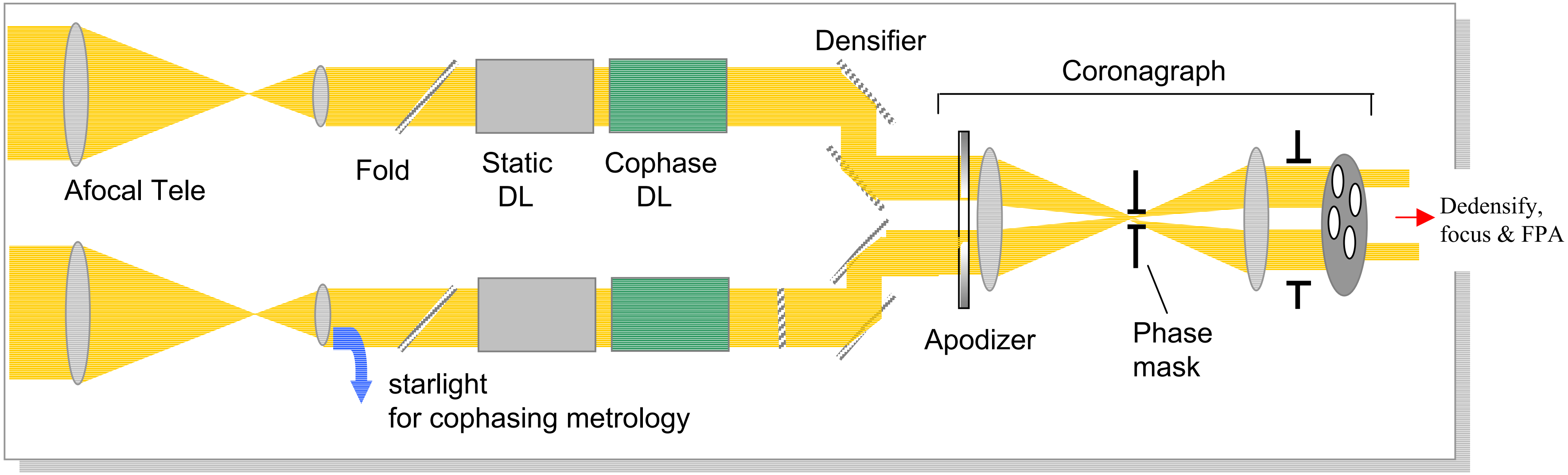
- Risk
  - We have identified major risk items for the NRLA system, and assessed them as performance, cost, and/or schedule risk items
- Reliability/robustness
  - The NRLA is a complex system; overall reliability will be a design driver and must be addressed during future design activities
- Science and Technology legacy
  - Hypertelescope concept and major technology components of the NRLA concept will provide heritage to future space observatories
- Availability of relevant precursor missions
  - The NRLA design concept is scalable: baseline, numbers/sizes of apertures, operational scenario can be optimized for both precursors and more advanced designs
  - SIM provides substantial contribution in the area of interferometric components
  - NGST provides cryo mechanism and wavefront control technology

NRLA Performance

- NRLA meets TPF draft science requirements
- System performance model predicts SNR vs time or time to SNR
  - Parametric with range, stellar type
  - Based on error model tied to simulation
  - Evaluated at wavelengths centered on TPF SWG Biomarker Report (DeMarais et. al.)
- Observing time budget vs draft science requirements shows:
  - Uses 54% of allocatable planet study time (=27% total mission time) if all targets at 30 pc
  - Includes initial detection, CO_2 & H_2O scans [R=20, SNR=10], O_3 & CH_4 scans [R=20, SNR=25]
  - Generous margin for additional revisits for orbit determination, additional study
- Observing time budget vs Exhibit II Goals shows:
  - Uses 97% of allocatable planet study time (=49% total mission time) if all targets at 20 pc
  - Includes all scans as above
- Based on sequential filtered spectroscopy scan
  - Observing efficiency increases if spectrometer added

How does NRLA work?

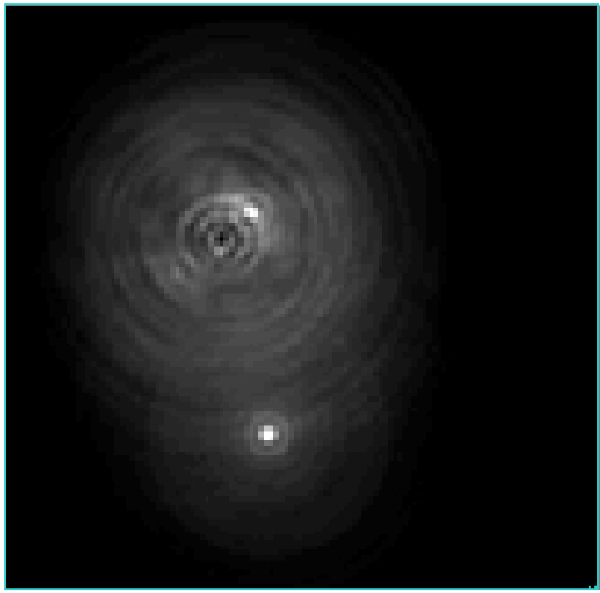
- Image formation in the NRLA:

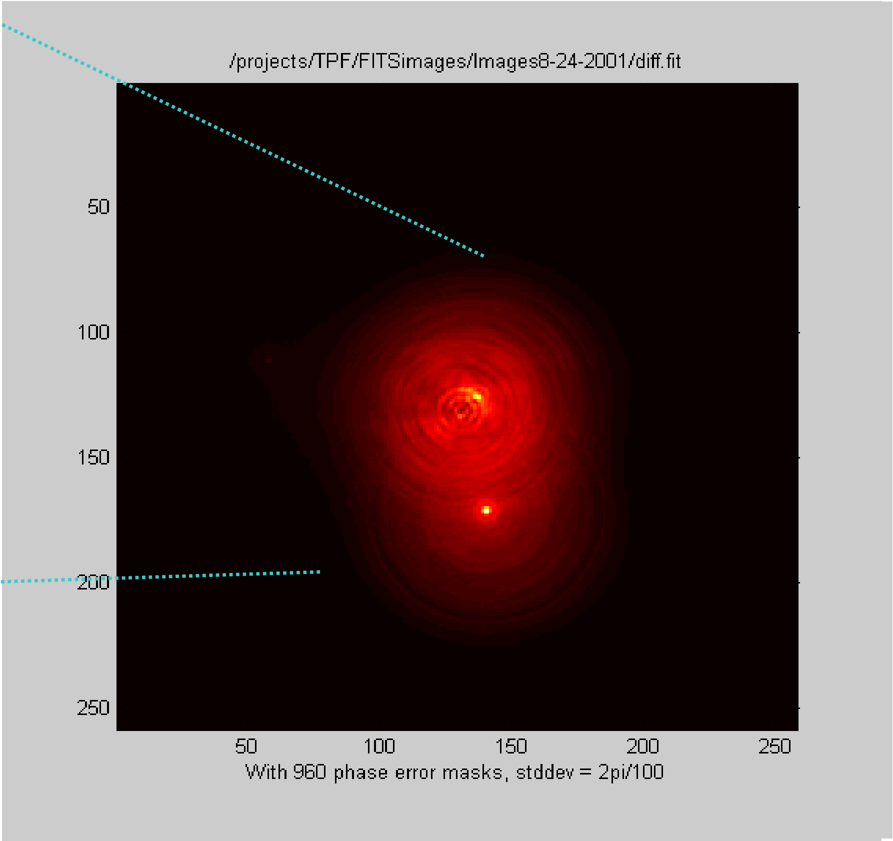


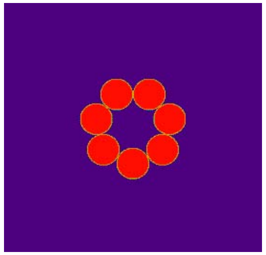
Collect light, Relay to DL → Apply fixed (Coarse) DL → Apply dynamic (fine) DL → Expand beams → Combine at densifier → Mask star at coronagraph → Redilute beams → Relay beams → Combine at Fizeau focus → Detect → Reconstruct Image → Remove Star residual

Example images from NRLA simulation

- Image of the system looking at a solar system, d=10pc, λ=10mm, $\Delta\lambda$ = 1mm; 2.7 hrs/160 snapshots





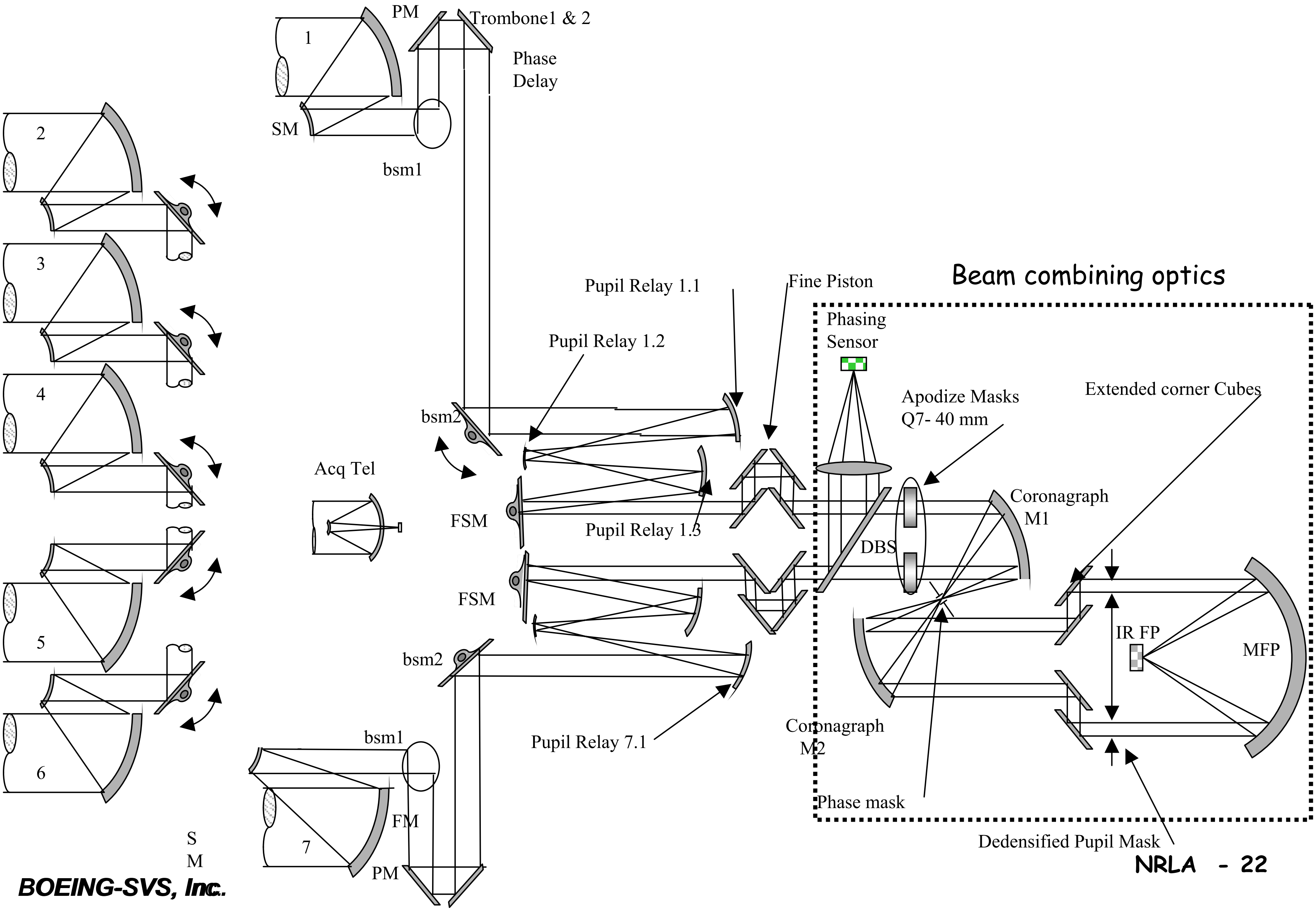


Densified pupil configuration

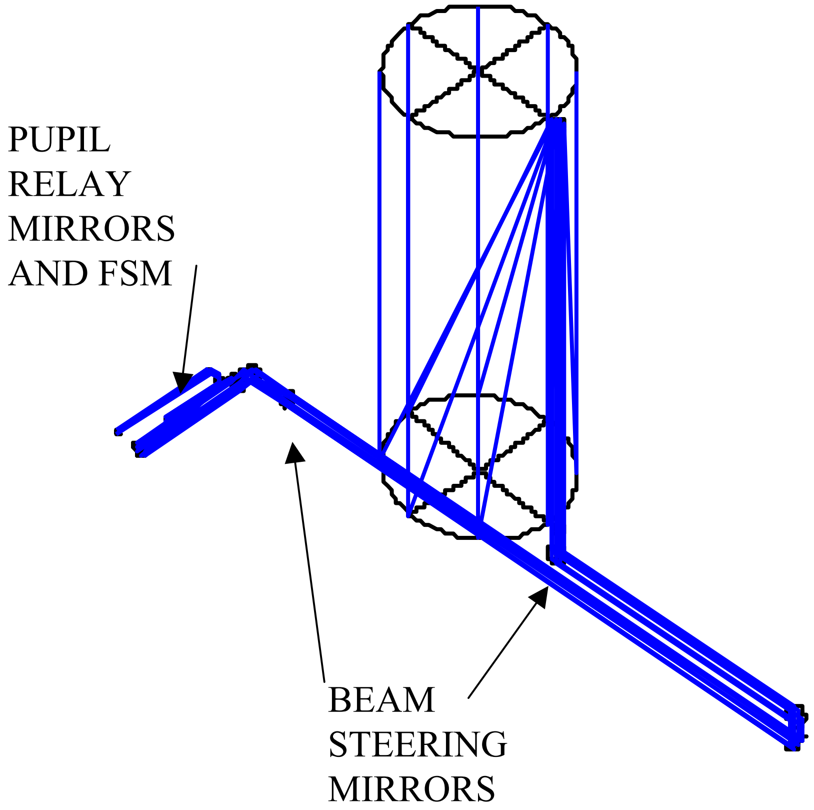
NRLA Optics Features

- OTAs: Mersenne off-axis, D=3m (point design)
- OTAs are feasible with existing technology (factored into mass budget)
  - Achieving lighter weight optics would be a plus
- Separate acquisition star finders for each telescope
- Each path has a coarse delay line within beam steering mirrors. After pupil reduction there is a fine delay line, redundant piston in powered pupil relay optics and FSM
  - Piston and tilt quantified using visible light split off at densified pupil
- Coronagraph imaging optics: efl 2.5 m with a 1:1 pupil relay. The actual efl is driven by the coronagraph physics and the PSF size needed to suppress the primary star
- A single mirror forms an image at the coronagraph then reimages the densified pupil plane to the de-densified pupil plane with a magnification of 1.
- Coronagraph physically small and can be built as a compact, well-controlled (thermally, mechanically) unit, and tested thoroughly on ground
- Pupil plane mask (required for coronagraph operation) is placed at the de-densified location
- The seven individual paths have an identical number of mirrors and mirror orientations

1.5.2 NRLA Optical Diagram

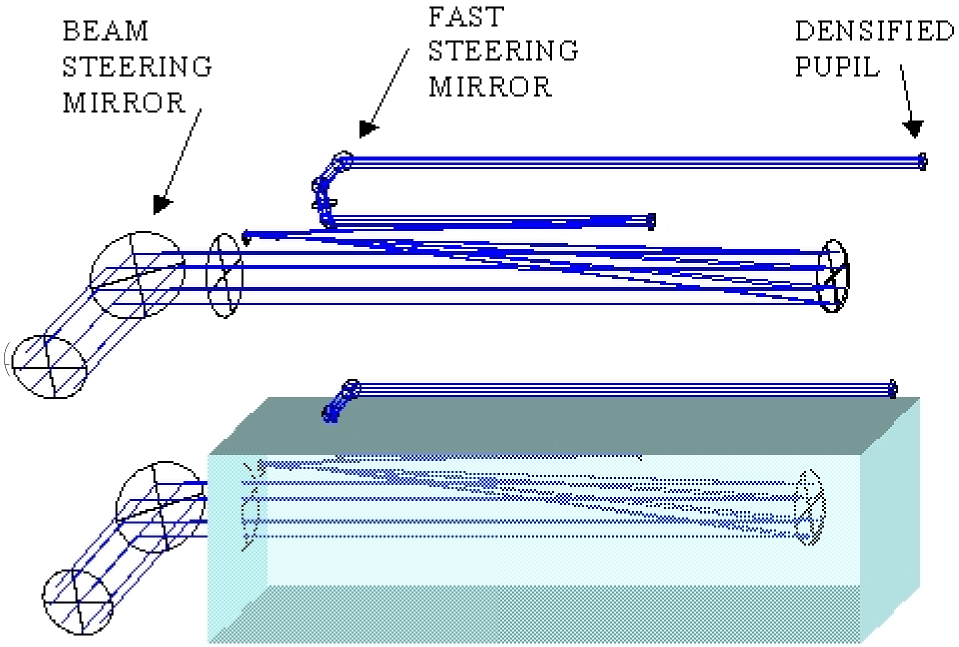


One of Seven Un-Obscured Mersenne Telescopes



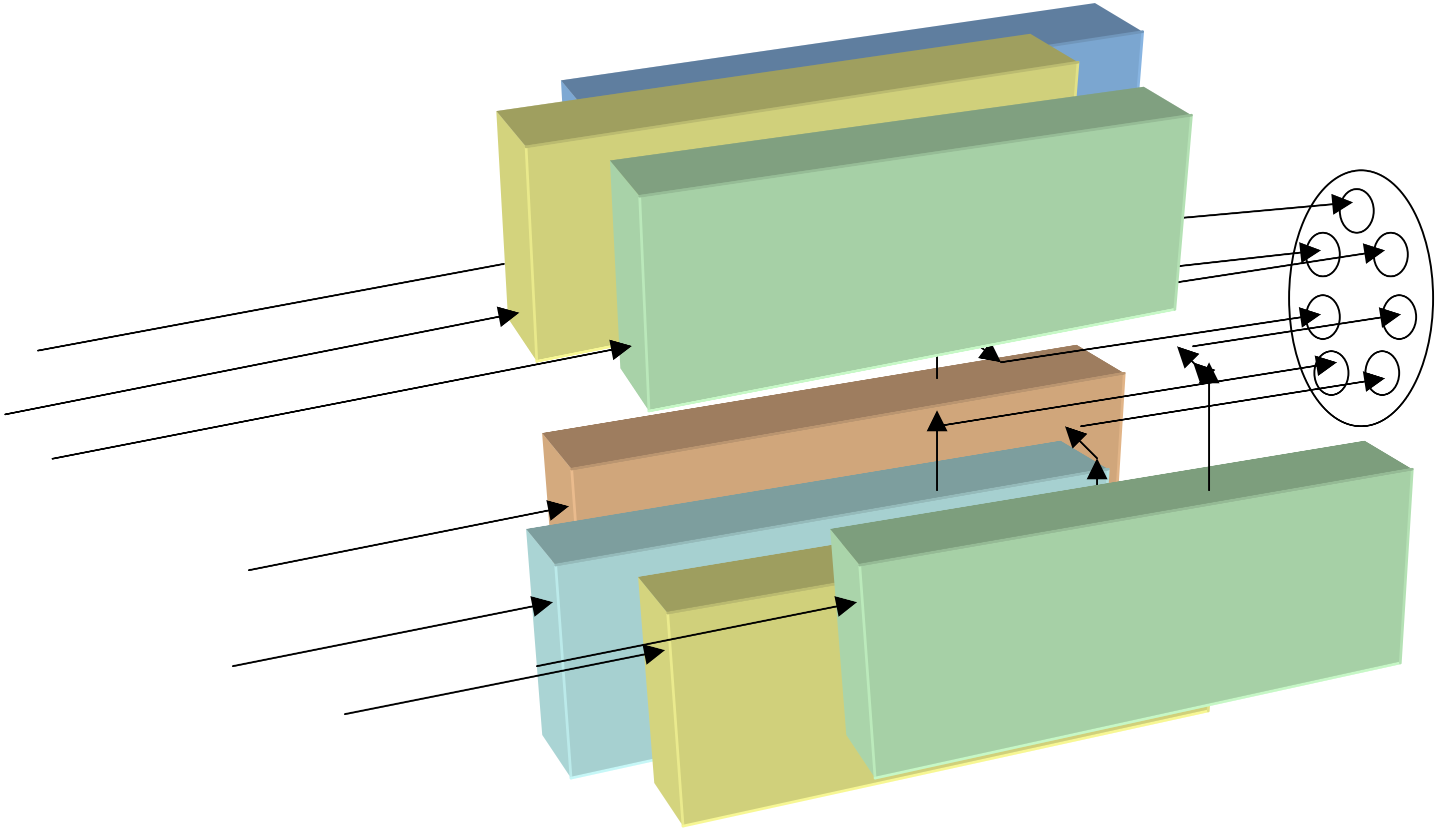
- 3 m f/3 primary from 6.6 m, f/1.25 parent
- Will Trade-off asphericity with surface smoothness requirements
- Telescope M = 15 with 200 mm beams through coarse trombones
- All telescopes paths to densified pupil are identical in mirror number and orientation to preserve polarization and amplitudes.
- Minimal number in design may be increased to optimize packaging
- Location of pupil relay package controlled by X and Y offsets of trombone mirrors

1.5.3 One of Seven Pupil Relays to Densified Pupil

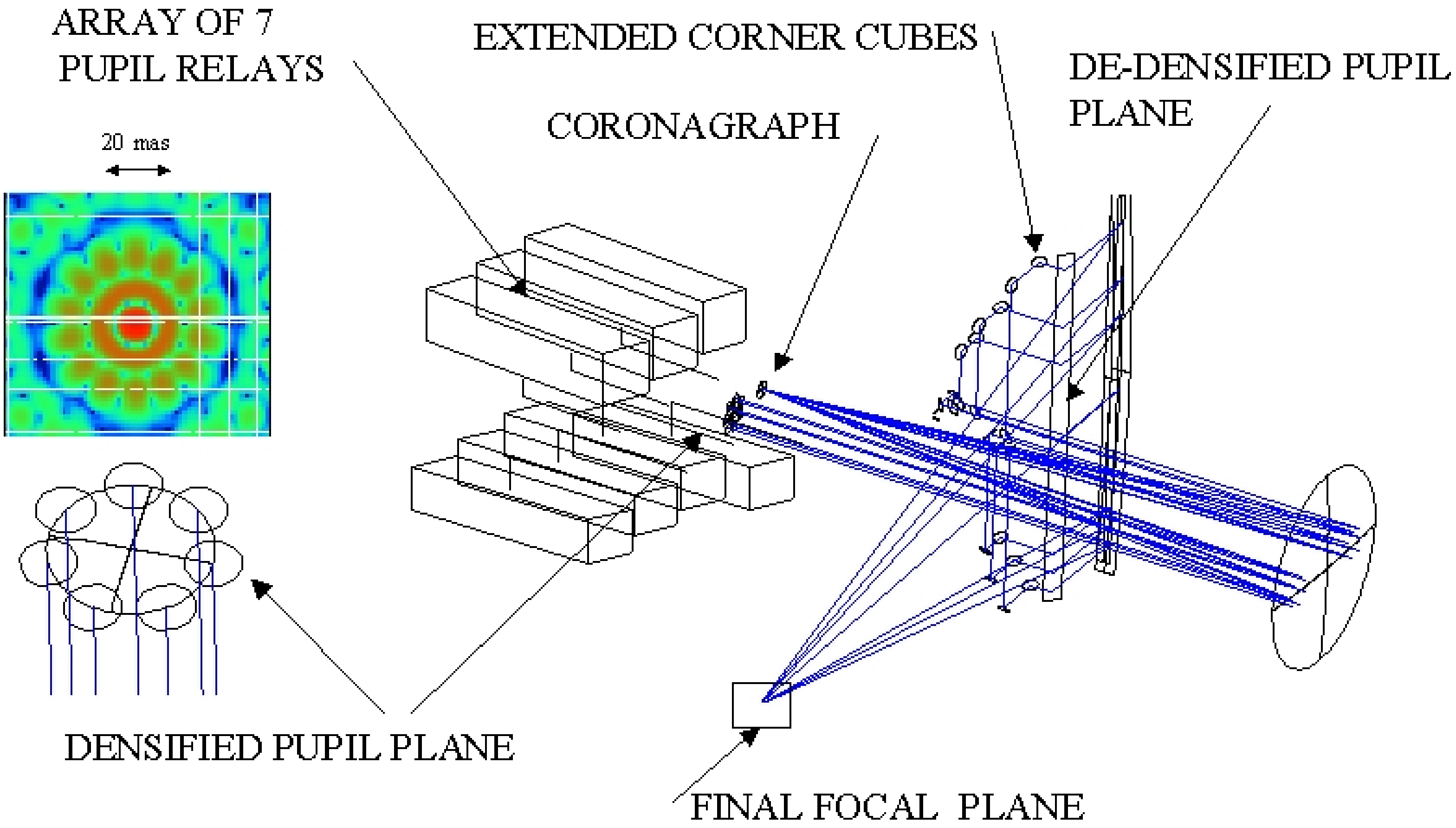


- Beam Steering Mirror located after Trombone optics
- 3 Relay Mirrors aspheric with terms to B6
- Fast Steering mirror is last mirror to fold system into densified pupil plane
- Second Mirror is less than 50 mm and can be used to provide 2-3 lambda piston
- Mirrors 4 and 5 hold pupil location primarily to meet tolerances at the de-densified pupil
- Seven pupil Relays housed in enclosure

Assembly of the Seven Pupil Relays to Form the Densified Pupil



Densified Pupil to Coronagraph to Restored Pupil to Image Plane



ARRAY OF 7
PUPIL RELAYS

EXTENDED CORNER CUBES

DE-DENSIFIED PUPIL
PLANE

CORONAGRAPH

20 mas

DENSIFIED PUPIL PLANE

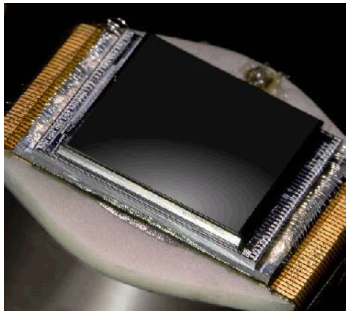
FINAL FOCAL PLANE

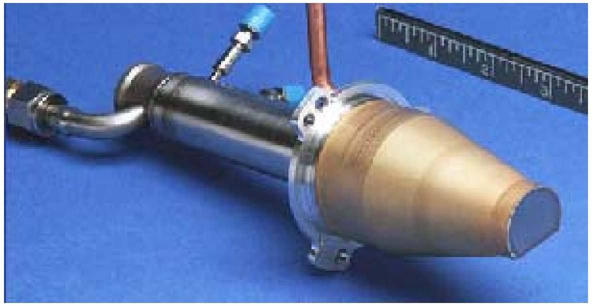
Optical Design from initial densified pupil to final de-densified pupil

- A single large mirror is used to form an image at the coronagraph then reimage the densified pupil plane to the de-densified pupil plane with a magnification of 1
- The pupil plane mask required for the coronagraph is at the de-densified location
- The seven individual paths have an identical number of mirrors and mirror orientations.
- Some tuning of sub-pupil locations possible with thermal control of ECC's
- Adjustment of the paths to remove piston errors accomplished by tilt of the extended corner cubes
- Final imaging optic is a strip from a long off axis asphere 50 mm wide and 1350 mm long
- Intermediate sub-aperture size of 40 mm diameter chosen as a compromise between:
  - Avoiding a second pupil relay between coronagraph and de-densified array
  - Keeping extended corner cubes to "manufacturable" size
  - Maintain throughput to coronagraph with FFOV of 50 microrads

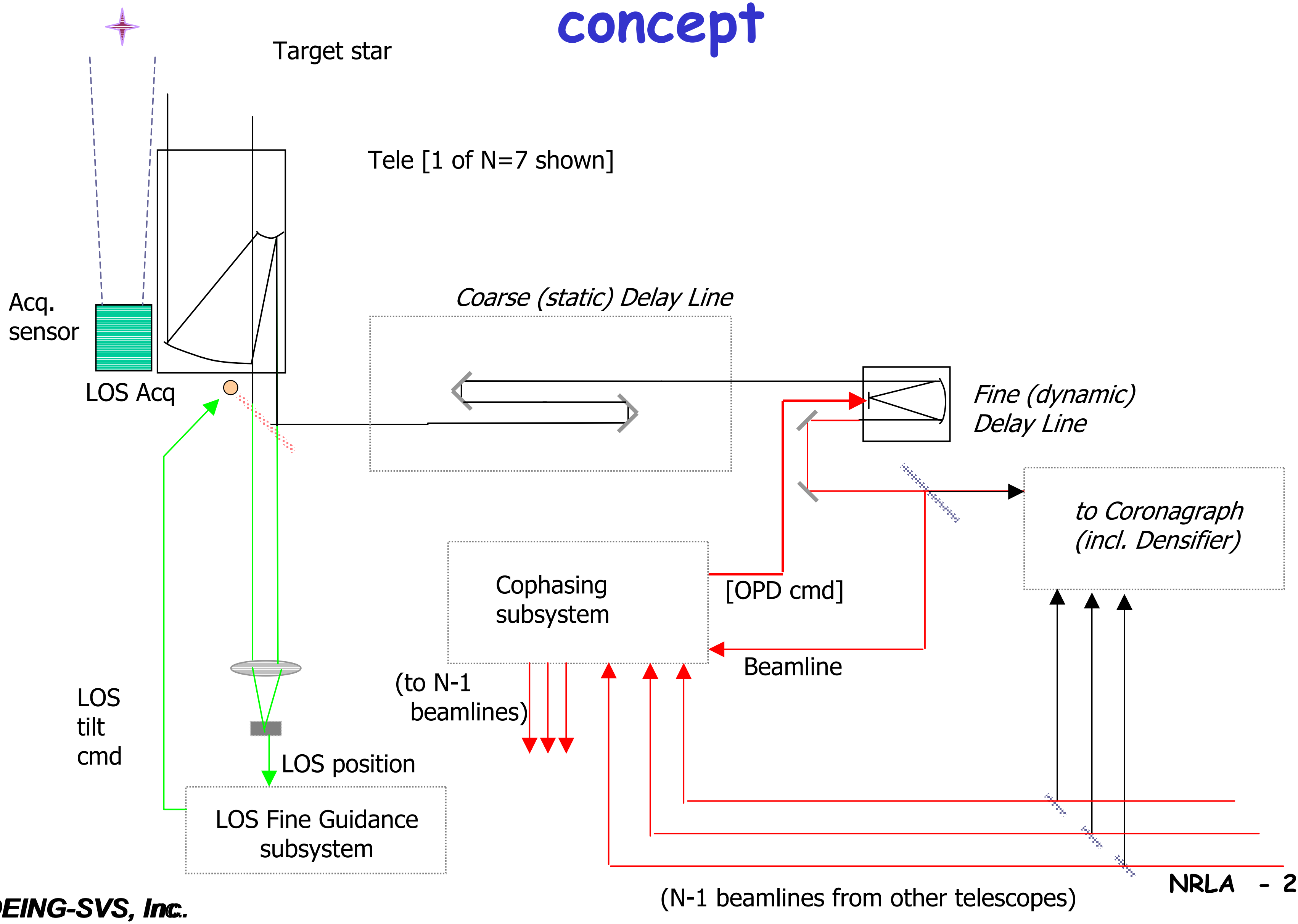
1.5.5 Detectors Will Be Able to Meet NRLA Requirements

- Operation temperature – detector & cold shield 10K
- Source of cooling – options: Turbo-Brayton or Sorption
  - Will need good localized thermal design for detector area
- Dark current – 1 e/sec (can tolerate higher)
- Array size –256 x 60 min.
- Readout noise – 5 e rms; quantification noise 5 e rms
- Several possible candidates
- Sources – DRS technologies (former Boeing/RI Sci Ctr)
  - Si:As BIB detectors; operational; some improvements in pixel size needed; possible with advanced Si:As BIB or hybrid array based on "Hawaii" mux
  - Si:Ga also possible
  - HgCdTe (17.4 µm cutoff) may be acceptable





NRLA: LOS control and aperture cophasing concept



Target star

Tele [1 of N=7 shown]

Acq. sensor

LOS Acq

Coarse (static) Delay Line

Fine (dynamic) Delay Line

to Coronagraph (incl. Densifier)

Cophasing subsystem

[OPD cmd]

Beamline

(to N-1 beamlines)

LOS tilt cmd

LOS position

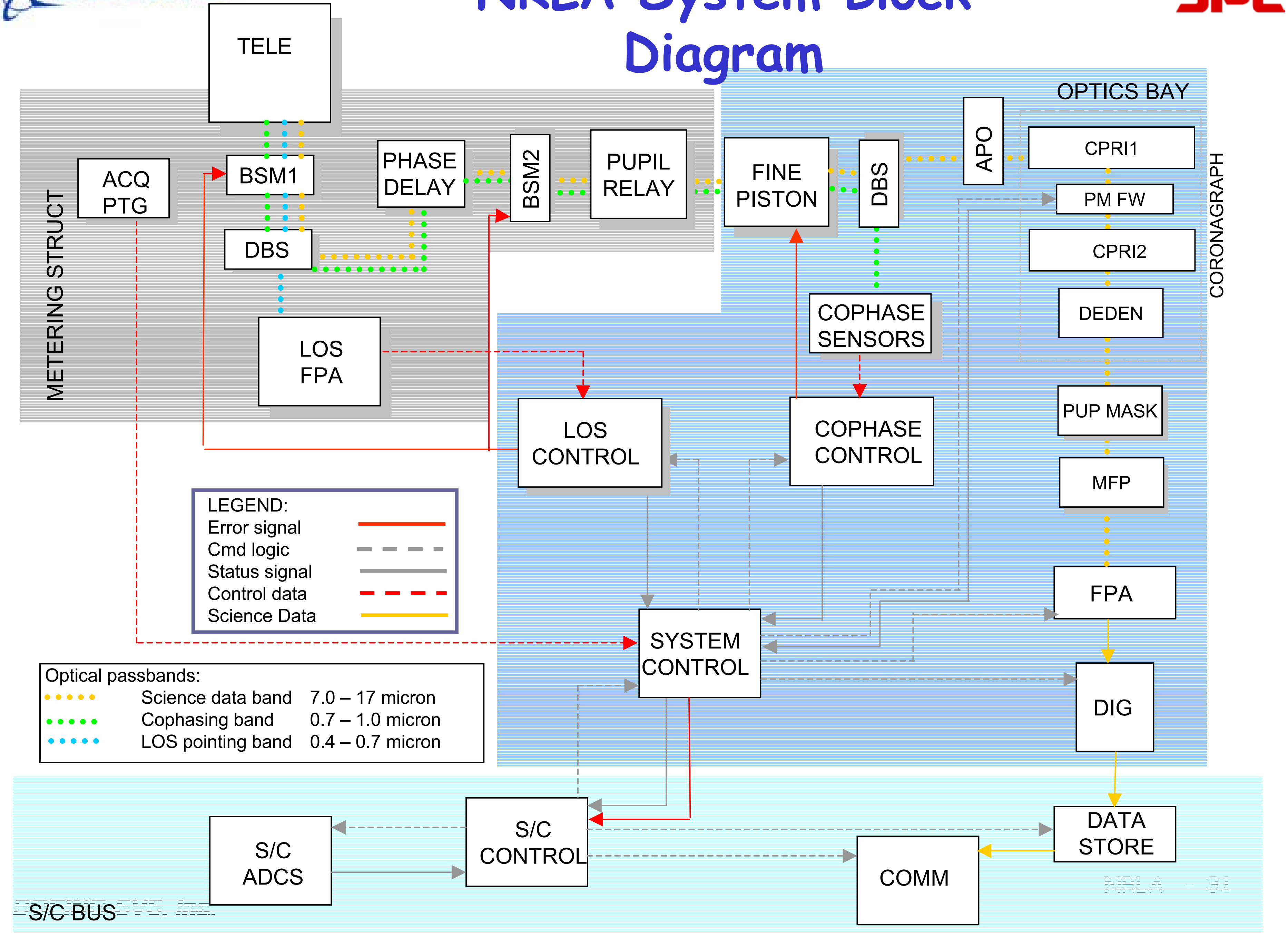
LOS Fine Guidance subsystem

(N-1 beamlines from other telescopes)

Concept for, and sequence of events, associated with co-phasing

- Basic Concepts & Assumptions:
  - Finite coherence length => interference fringe peak maximizes when OPD = 0
  - Fringe contrast is Gaussian function of OPD with DC offset
  - (A is cophased with B) and (B is cophased with C) => (A is cophased with C)
- Cophasing approach:
  - Closed loop tip/tilt control established for optimal interference detection.
  - Wavefront from one OTA selected as point of reference.
  - Open loop piston raster scan with each other wavefront over coherence window until fringe maximum is established.
  - An incremental estimator based on the known Gaussian fringe profile is used to for fringe acquisition.
  - Once a wavefront is cophased with the reference, control for that wavefront is passed to cophasing maintenance function while fringe acquisition proceeds for the other wavefronts.
  - Telescope is cophased when all wavefronts are under cophasing maintenance.

NRLA System Block Diagram



LEGEND:

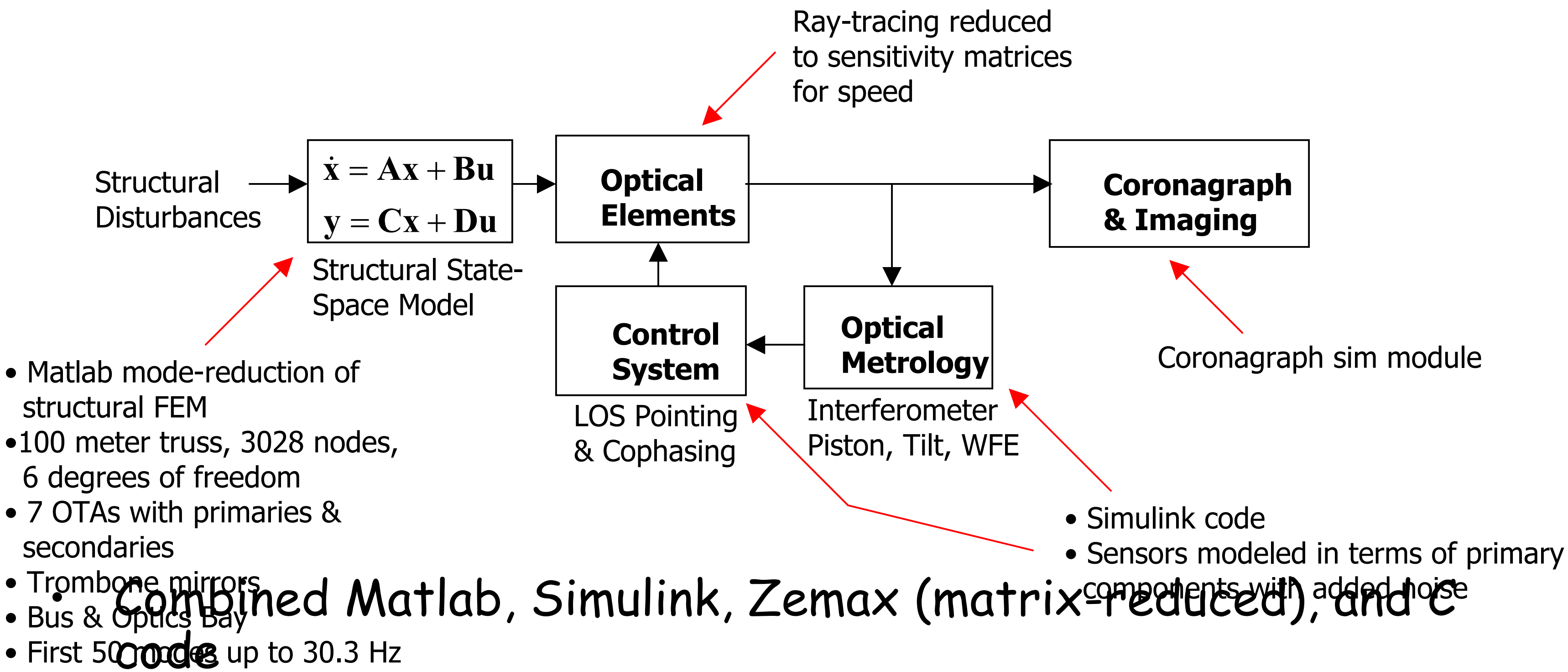
Error signal	━━━
Cmd logic	– – –
Status signal	━━━
Control data	‒ ‒ ‒
Science Data	━━━

Optical passbands:

• • • • •	Science data band	7.0 – 17 micron
• • • • •	Cophasing band	0.7 – 1.0 micron
• • • • •	LOS pointing band	0.4 – 0.7 micron

1.6 Computer models of the NRLA (1)

- Model Schematic:



Ray-tracing reduced to sensitivity matrices for speed

Structural Disturbances

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u}$$
$$\mathbf{y} = \mathbf{C}\mathbf{x} + \mathbf{D}\mathbf{u}$$

Structural State-Space Model

Optical Elements

Coronagraph & Imaging

Control System

Optical Metrology

Coronagraph sim module

LOS Pointing & Cophasing

Interferometer Piston, Tilt, WFE

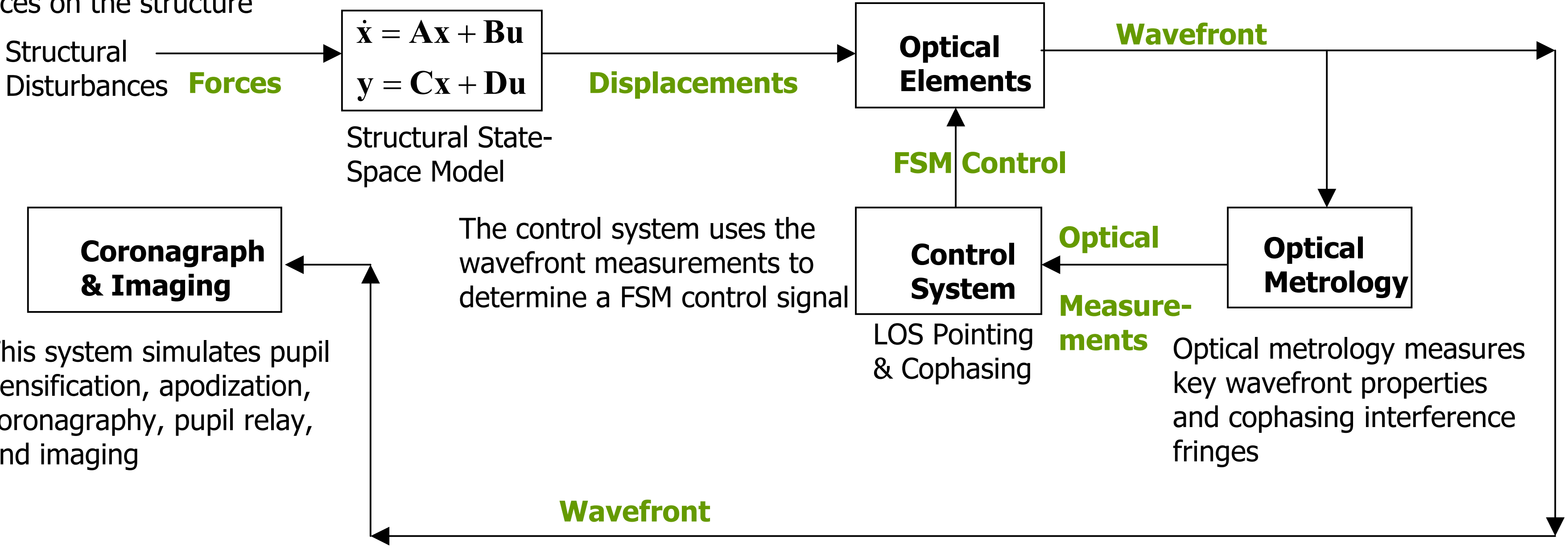
- Matlab mode-reduction of structural FEM
- 100 meter truss, 3028 nodes, 6 degrees of freedom
- 7 OTAs with primaries & secondaries
- Trombone mirrors
- Bus & Optics Bay
- First 50 modes up to 30.3 Hz

- Simulink code
- Sensors modeled in terms of primary components with added noise

- Combined Matlab, Simulink, Zemax (matrix-reduced), and C code
- Currently runs under Windows, but can be ported to Unix

Computer models of the NRLA (2)

- Data Flow:



Structural disturbances are input as a time series of forces on the structure

Structural Disturbances **Forces**

The state-space model produces a time series of displacements for key optical elements

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u}$$

$$\mathbf{y} = \mathbf{C}\mathbf{x} + \mathbf{D}\mathbf{u}$$

Structural State-Space Model

Displacements

The optical model generates the wavefront and associated phase errors from each OTA

Optical Elements

Wavefront

FSM Control

The control system uses the wavefront measurements to determine a FSM control signal

Control System

LOS Pointing & Cophasing

Optical Measure-ments

Optical Metrology

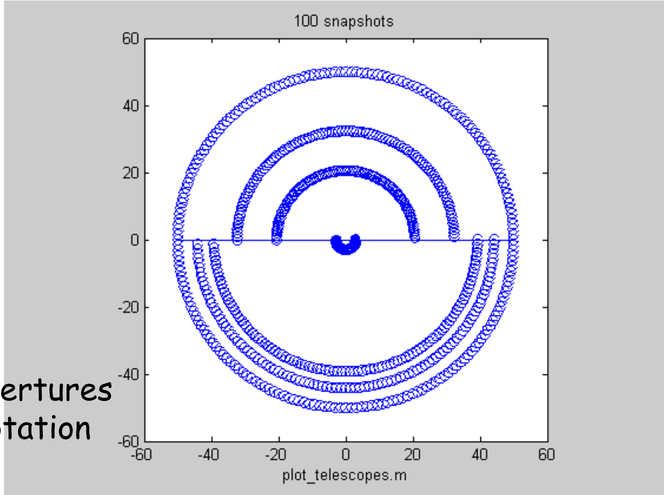
Optical metrology measures key wavefront properties and cophasing interference fringes

Wavefront

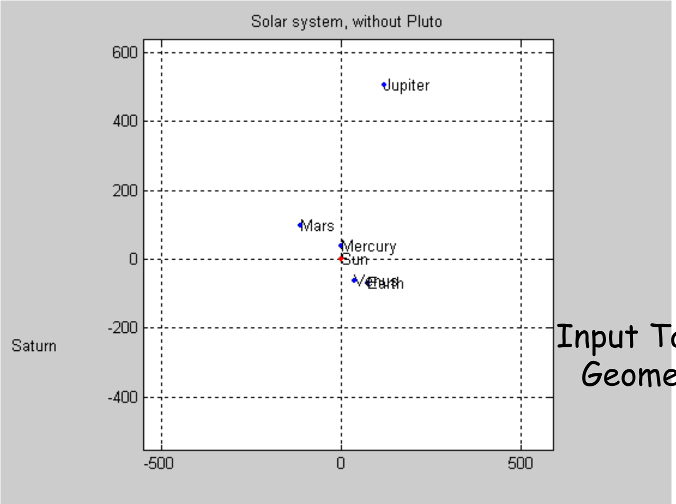
Coronagraph & Imaging

This system simulates pupil densification, apodization, coronagraphy, pupil relay, and imaging

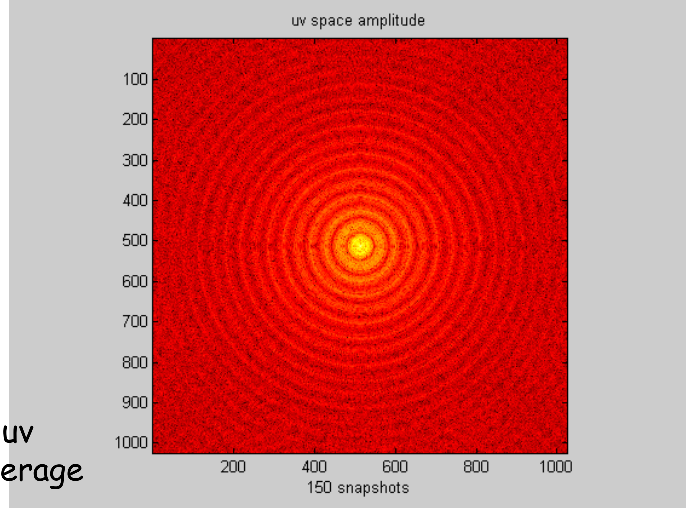
Coronagraph Simulation Examples



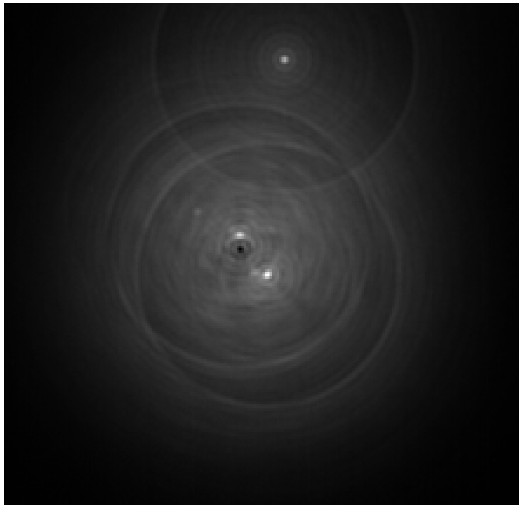
Map of Apertures
during rotation



Input Target
Geometry



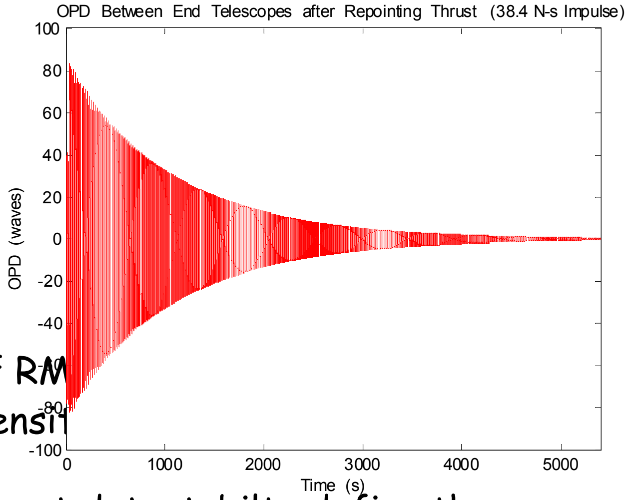
uv
coverage



Output
Image

The model identifies driving subsystem requirements

- Requirements driven by slew & settle constraints:
  - Simulate structural disturbances consistent with braking after repointing.
  - Measure time to reacquire interference fringes as a function of sensor sensitivity and control & structural parameters.
  - Parameter values required to meet mission time constraints define the requirements.



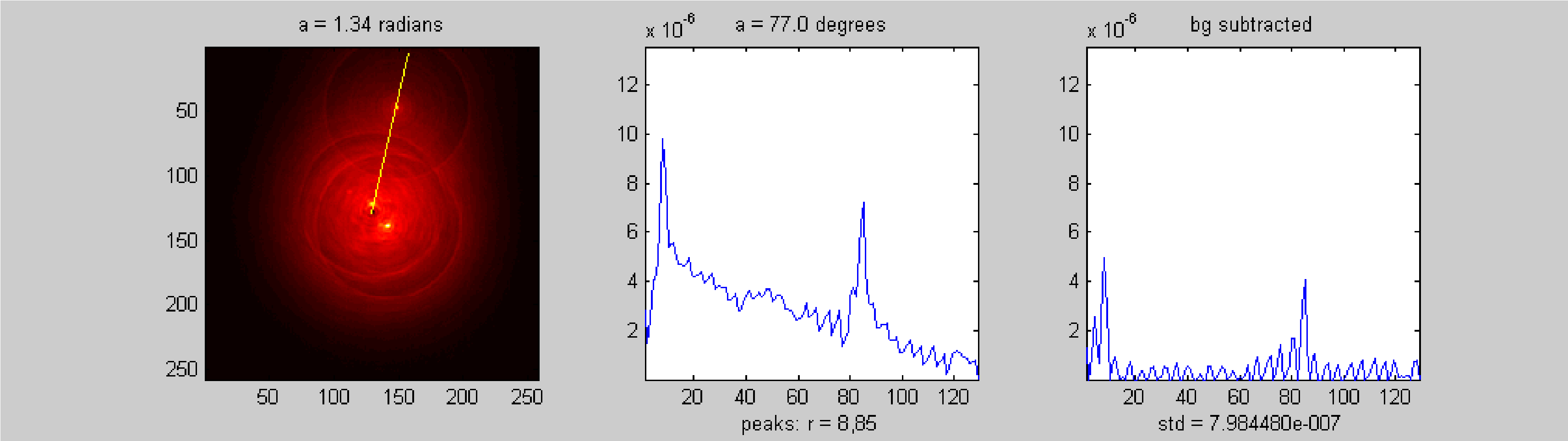
- Requirements driven by RMS WFE:
  - Simulate planet detectability as a function of RM
  - Measure RMS WFE as a function of sensor sensi parameters.
  - Parameter values required to meet mission planet detectabilty define the requirements.

The model is used to create error budgets

- Planet detectability as a function of the RMS WFE is used to determine the WFE budget
- In turn, the error budget for sensor sensitivities and control & structural parameters is determined by their simulated effect on the RMS WFE

Model Outputs are being used for detailed performance studies

- Example: Planet detection – sample radial image profile



  - Results also include detectability as a function of RMS WFE and probability of false detection

Plans for Further Model Development

- Currently:
  - Only 4 OTAs currently in the optical model, although all 7 are in the structural model
  - Phase error creation is only physically simulated for 4 wavefronts. The others must be estimated.
  - No thermal modeling included in the wavefront control
  - Low fidelity modeling of all sensors
  - Full ray-tracing optical modeling is reduced to sensitivity matrix approximations for computational speed
- Future Enhancements
  - Model the optics for all OTAs
  - Add thermal considerations into the simulation
  - Increase fidelity of sensor models
  - Add more detailed mode logic to simulate full mission scenarios

Tolerances and Error Budgets

- How derived: System performance model:
  - Analytical derivation w/some empirically-derived scale factors based on simulation
  - Circular Phase Mask assumed
  - Includes both interferometer and coronagraph performance:
    - Leakage terms (several factors), LOS pointing, Cophasing, H.O. WFE, straylight & thermal background, zodi/exozodi, FPA terms
- Coronagraph leakage results in an extended background (star residual) in the synthesized image; this is reduced with rotational PSF reduction, reduction factor is sqrt(no. snapshots)
- Reduce all terms to net e [rms] using observing time + star/planet specs.
  - Detected photoelectrons at FPA
  - Computation of signal photoelectrons allows SNR computation
  - Use SWG Biomarker Report (24 May 2001, D. De Marais et. al.) to get appropriate spectral bands for evaluating SNR

Error Budget w/ Allocations

Noise [e, rms]

- **Star leakage** 1746
  - **Intrinsic (finite star size)** 39
  - **Bandpass (chromatic PSF size)** 204
  - **Optics (H.O.) WFE** 982
  - **Beamline Cophasing** 297
  - **PSF misalignment (array LOS pointing)** 30
  - **LOS jitter (indiv. Beamlines)** 1377
  - **Amplitude imbalance** 0 [not alloc.]
  - **Coronagraph errors**
    - **-- mask radius error** 6
    - **-- mask thickness error** 7
    - **-- misfocus (thermal distortion)** 234
- **Unwanted radiation** 1428
  - **Fore-optic scatter** 44
  - **Thermal emission**
    - **-- optics + structure** 1419
  - **Local zodi** 152
- **Source Shot noise** 140
  - **Signal (planet)** 139
  - **Exozody** 18
  - **Image reconstruction noise**
    - **-- spatial clutter**
    - **-- cleaning**

    [Tech. Dev. Item]
- **Sensor noise** 128
  - **Read noise** 61
  - **Quant. Noise** 61
  - **Dark current** 95

Net leakage has a sqrt(Nss) improvement factor due to rotational PSF subtraction; Nss = number of snapshots

G5V at 30 PC
Planet radius = 1 RE, albedo = 0.39 (T = 300K)
Continuum at 8.67 microns
150 snapshots, rotation period = 5hr
Total observation time = 2.5 hr
Coronagraph type
circular Phase mask

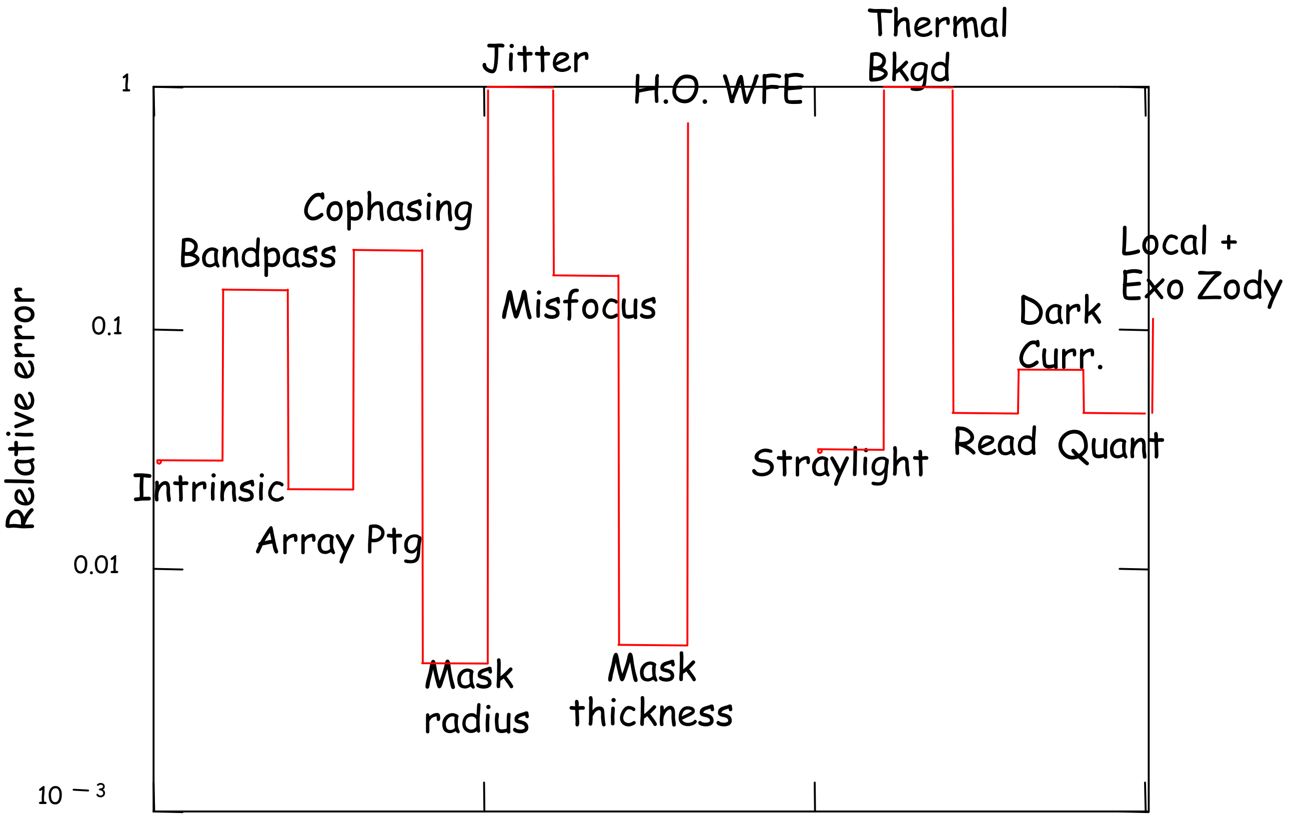
Planet signal = 19274 e

System Specs For Example Error Budget

- Wavelength = 8.67 microns, R=3
- N=7 apertures, D = 3.0 m, B=baseline=100m
- System efficiency = 0.4 [= net transmission x QE]
- Optics WFE: λ/120 rms
- Cophasing piston error: λ/120 rms
- Array mispointing error: 35 nrad rms
- Individual beamline angular jitter: 25 nrad rms
- Temperature: Optics/Structure = 100K; cold shield (f/8 cone) 10K at FPA
- Thermal gradient in coronagraph: 0.5K longitudinal, 1 K radial
- Coronagraph mask error [circular phase mask assumed]:
  - 0.1% radial size error, 0.1% thickness error
- Read and quantization noise, 5 e rms each per sample
- Dark current: 1 e/sec-pixel
- Local zodi: per TPF book, scaled for wavelength using 286K BB spectrum
- Stray light: net BSDF = 10^6 x star irradiance at entrance pupil per IFOV
  - IFOV used = (λ_0/B) in reconstructed image, λ_0 = mean wavelength
- Not allocated yet: amplitude mismatch, image cleaning

Relative Error Budget Contributors – Example

- LOS jitter, thermal background, optics WFE, and cophasing are the largest contributors



CASE0: R=3, SNR=5, G5, 30pc

NRLA Can Meet Exhibit II Science Requirements

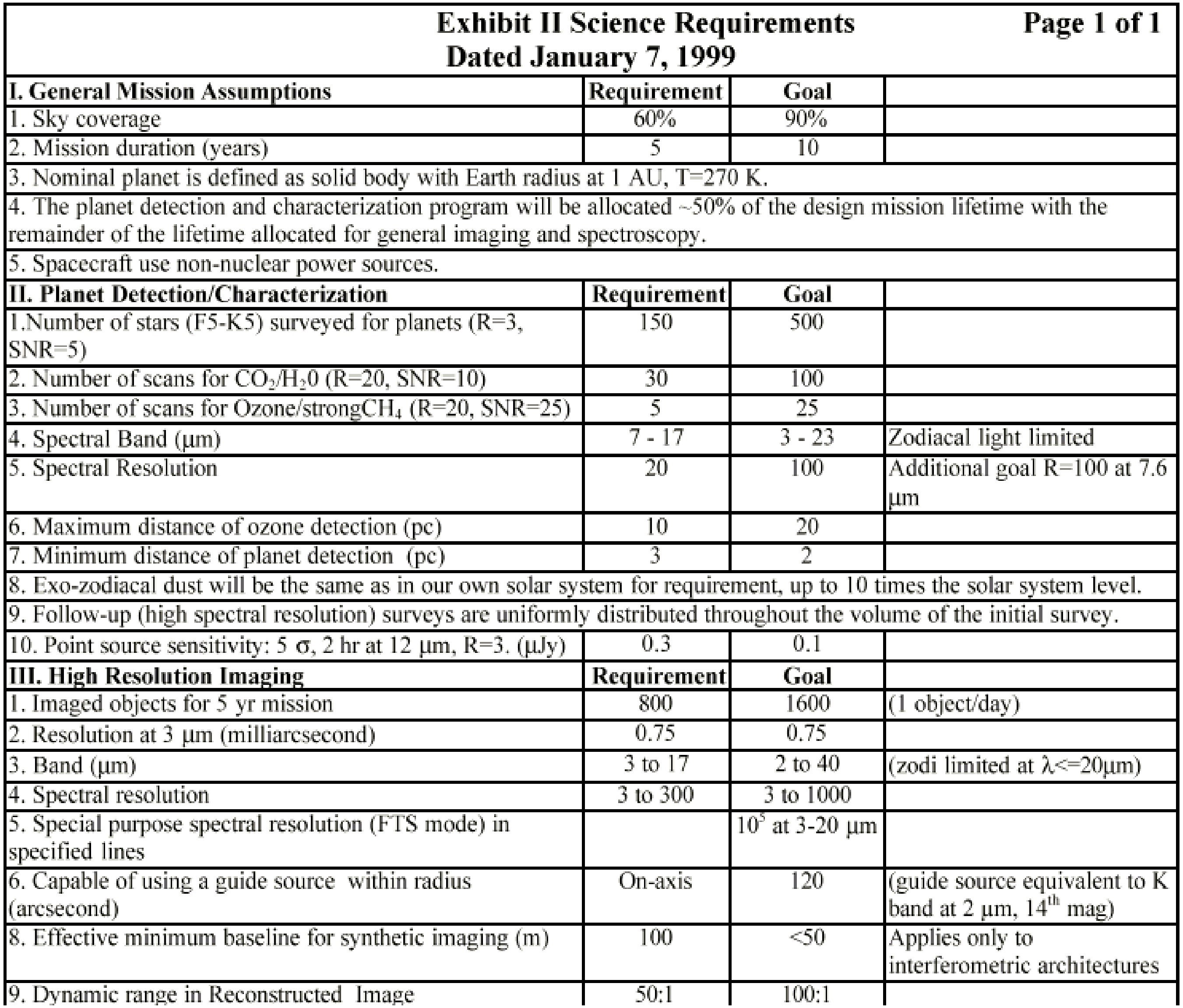
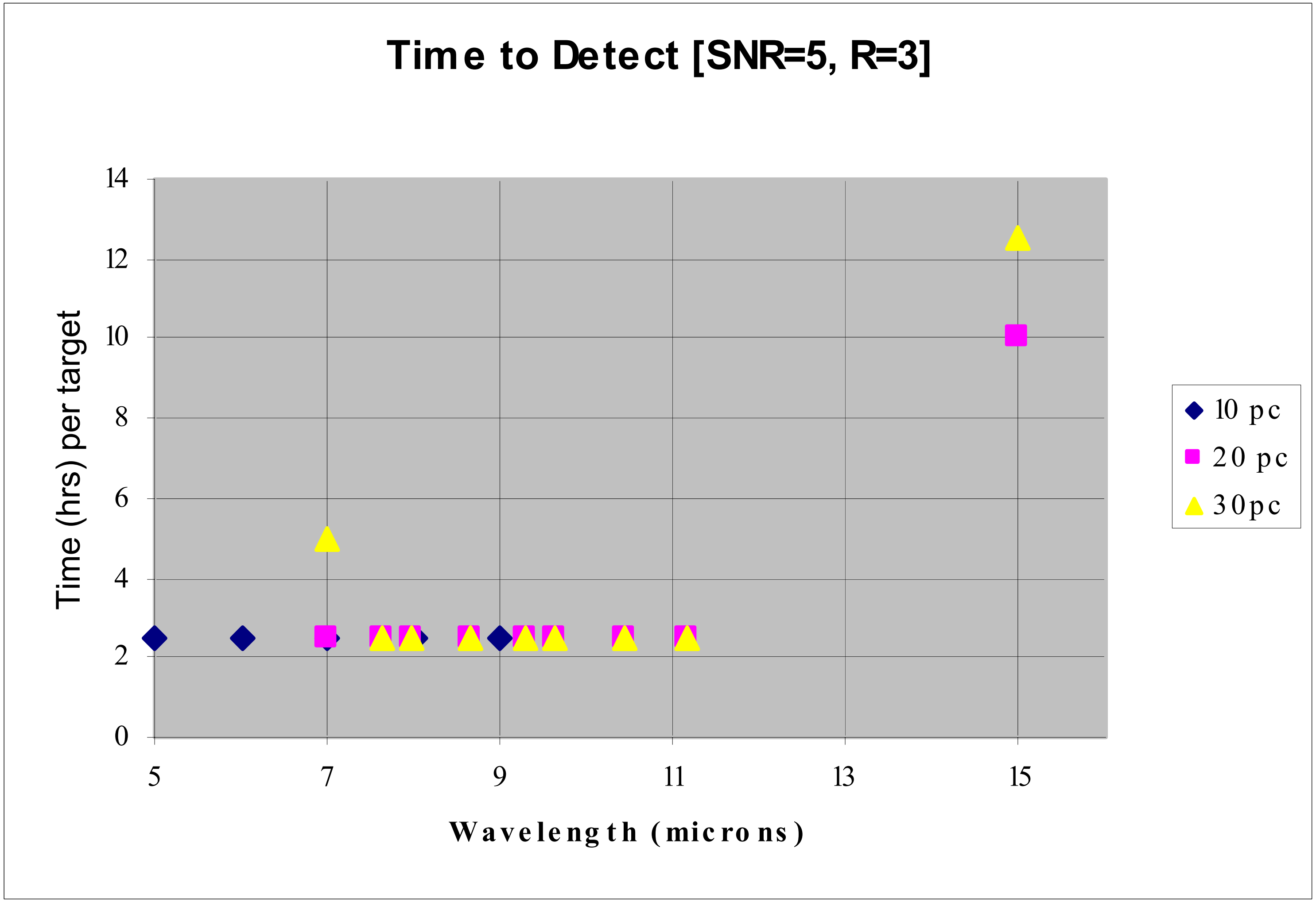


Exhibit II Science Requirements **Dated January 7, 1999**			**Page 1 of 1**
I. General Mission Assumptions	**Requirement**	**Goal**	
1. Sky coverage	60%	90%	
2. Mission duration (years)	5	10	
3. Nominal planet is defined as solid body with Earth radius at 1 AU, T=270 K.			
4. The planet detection and characterization program will be allocated ~50% of the design mission lifetime with the remainder of the lifetime allocated for general imaging and spectroscopy.			
5. Spacecraft use non-nuclear power sources.			
II. Planet Detection/Characterization	**Requirement**	**Goal**	
1.Number of stars (F5-K5) surveyed for planets (R=3, SNR=5)	150	500	
2. Number of scans for CO$_2$/H$_2$0 (R=20, SNR=10)	30	100	
3. Number of scans for Ozone/strongCH$_4$ (R=20, SNR=25)	5	25	
4. Spectral Band (µm)	7 - 17	3 - 23	Zodiacal light limited
5. Spectral Resolution	20	100	Additional goal R=100 at 7.6 µm
6. Maximum distance of ozone detection (pc)	10	20	
7. Minimum distance of planet detection (pc)	3	2	
8. Exo-zodiacal dust will be the same as in our own solar system for requirement, up to 10 times the solar system level.			
9. Follow-up (high spectral resolution) surveys are uniformly distributed throughout the volume of the initial survey.			
10. Point source sensitivity: 5 σ, 2 hr at 12 µm, R=3. (µJy)	0.3	0.1	
III. High Resolution Imaging	**Requirement**	**Goal**	
1. Imaged objects for 5 yr mission	800	1600	(1 object/day)
2. Resolution at 3 µm (milliarcsecond)	0.75	0.75	
3. Band (µm)	3 to 17	2 to 40	(zodi limited at λ<=20µm)
4. Spectral resolution	3 to 300	3 to 1000	
5. Special purpose spectral resolution (FTS mode) in specified lines		10^5 at 3-20 µm	
6. Capable of using a guide source within radius (arcsecond)	On-axis	120	(guide source equivalent to K band at 2 µm, 14th mag)
8. Effective minimum baseline for synthetic imaging (m)	100	<50	Applies only to interferometric architectures
9. Dynamic range in Reconstructed Image	50:1	100:1	

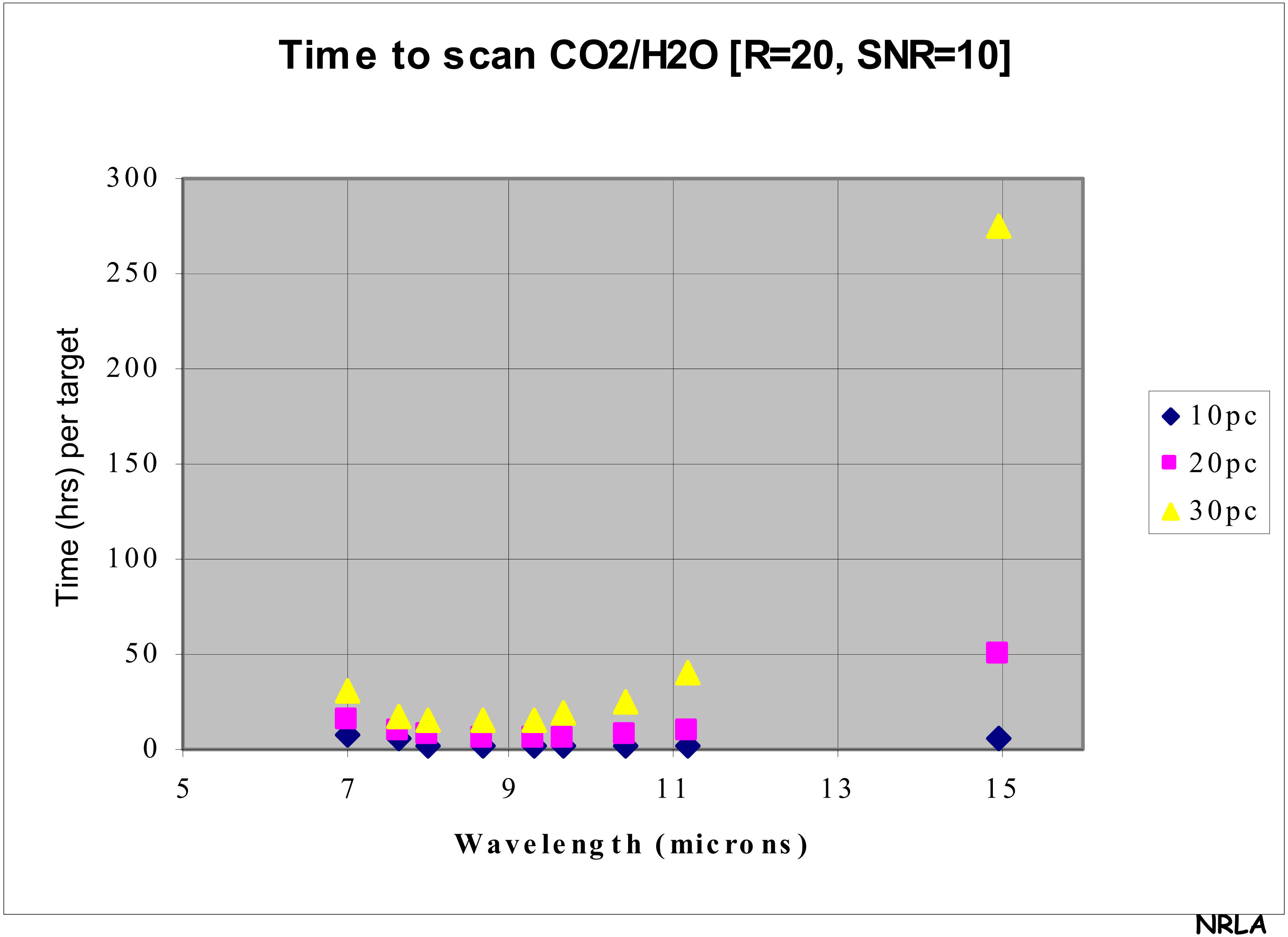
Error Budgeting Process

- Define a standard case as default for assessment:
  - K5V star at 30 PC
  - 1 earth at orbital radius consistent with T = 300K
  - Both emitted + reflected light from planet (albedo = 0.39)
  - 1 Exozodi per TPF book, local zodi at 1 AU (L2 orbit assumed)
  - NRLA period = 5 hours, 150 snapshots at 60 sec. Integration each
- Adjust individual error levels to get SNR required for this case
  - Balance 3-4 largest contributors
  - Some rebalancing possible for design flexibility
- Evaluate at R=3,20, SNR=5,10,25
  - Use wavelengths from SWG Biomarker report, 7 – 17 micron

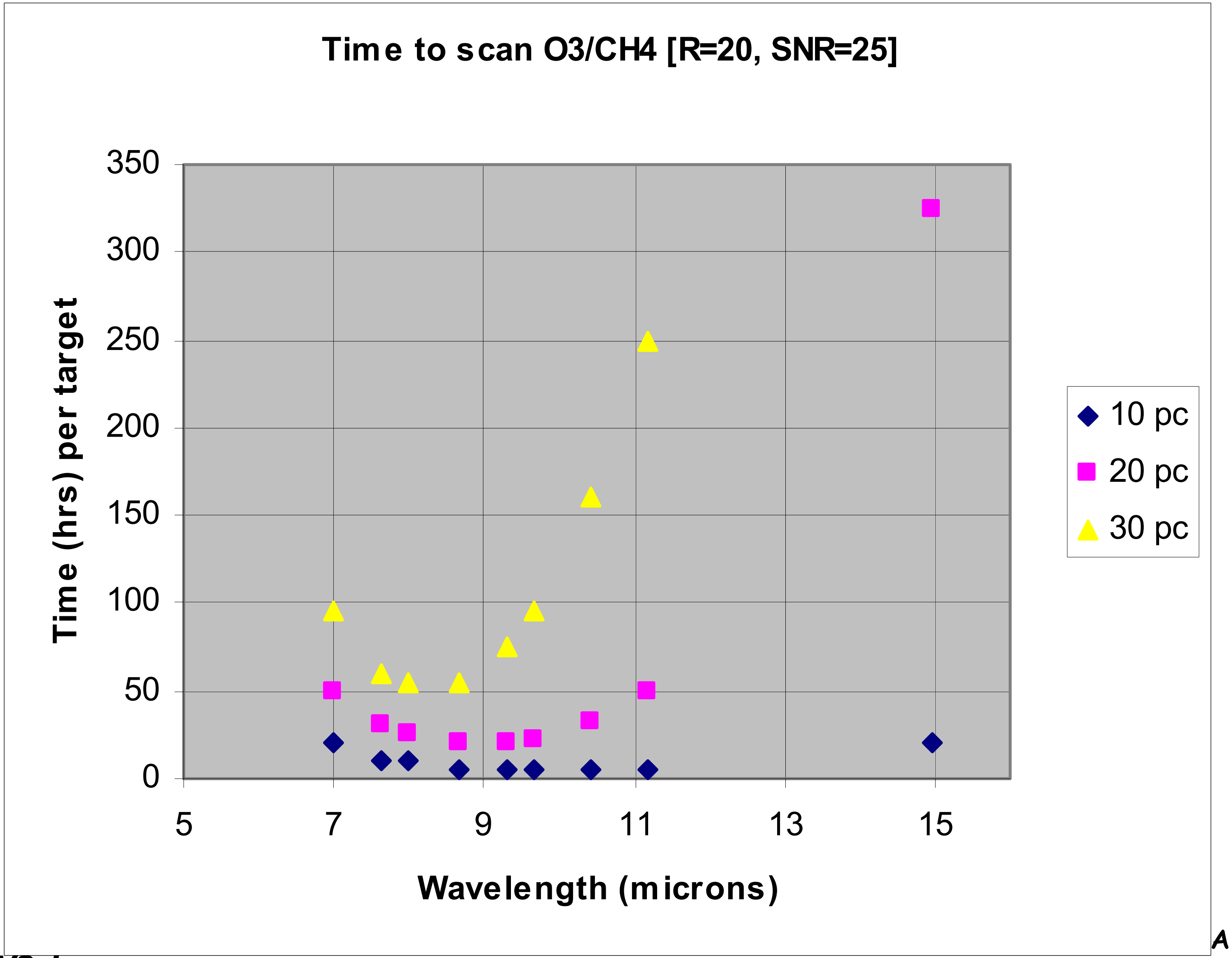
NRLA Observing Times vs Requirements (1)



NRLA Observing Times vs Requirements (2)



NRLA Observing Times vs Requirements (3)



NRLA Observing Time Budget

Objective		Total Time at d=10 pc	d=20 pc	d=30 pc
REQUIREMENTS				
Initial Detection	[150]	1875	1875	1875
CO2+H2O scans	[30]	1500	3000	6900
O3+CH4 scans	[5]	350	1000	3050
Total time		3725	5875	11825
Available (planet study only, 50%)		21900	21900	21900
Fraction used		0.17 [0.45 yr]	0.27 [0.7 yr]	0.54 [1.4 yr]
GOALS				
Initial Detection	[500]	6250	6250	6250
CO2+H2O scans	[100]	5000	10000	23000
O3+CH4 scans	[25]	1750	5000	15250
Total time		13000	21250	44500
Available (planet study only, 50%)		21900	21900	21900
Fraction used		0.59 [1.5 yr]	0.97 [2.4 yr]	2.03 [5.1 yr]

Notes: times are in hours; includes slew/settle time; sequential detection process
4 bins per band for molecular bands

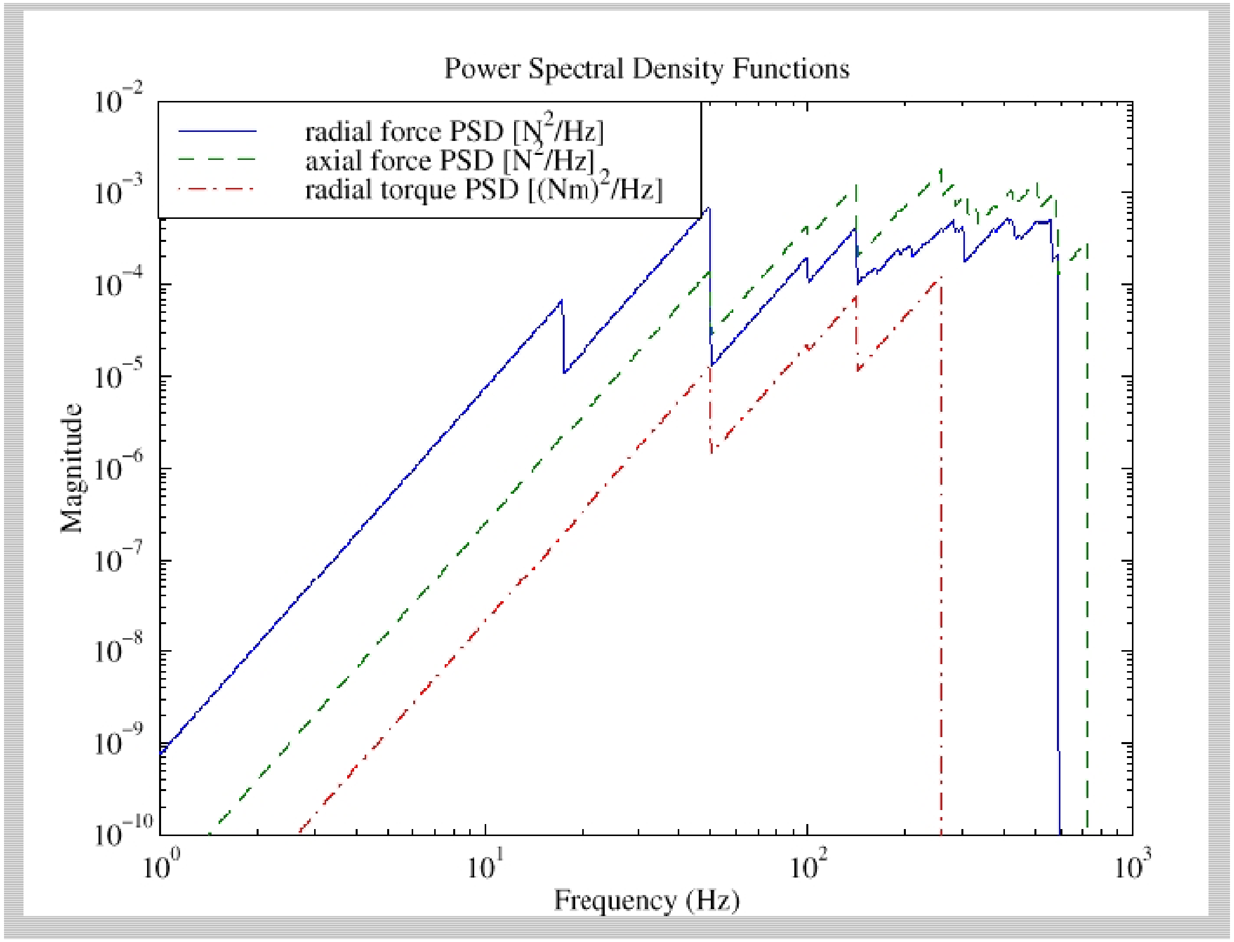
1.5.4 Loads Analysis Identifies RWA Disturbance as Primary Design Driver

- Nominal Rotation Rate ← Unimportant (Stretching > 0.021 Hz)
- Slew ← Unimportant (Bending > 0.011 Hz)
- Gravity Gradient ← Bounded by Slew
- RWA Disturbance PSD ← Design Driver (Bending > 0.061 Hz)
- Other possible sources
  - Sub-micron scale material and joint nonlinearities (a.k.a. "microdynamics") => Not considered as Level 0 design drivers
- Thermal
  - Uneven shielding and shadowing, CTE heterogeneity
  - Not considered as Level 0 design drivers

RWA Disturbance PSD Used as Primary Design Driver

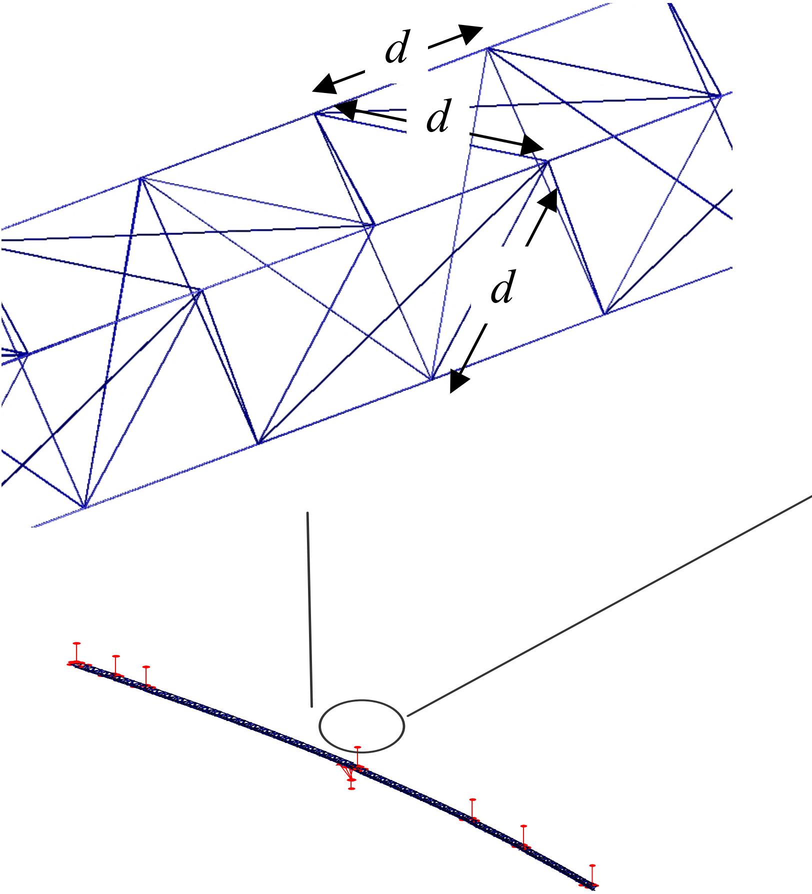
- PSD of Hubble RWA
- Used to define an upper bound worst cases for TPF design

$$E\left[F^{2}\right]=\int_{0}^{\infty}S_{f}(f)\,df$$



1.5.14 Triangular Truss Used for Baseline Truss Geometry

- Assume 15% parasitic node mass
- Rigid connections to OTA and Spacecraft lumped inertias
- Truss Properties (uniform over entire truss
  - Generic CFRP (E=97 Gpa)
  - 1 meter bay dimension
  - 6 cm diameter
  - 2.5 mm wall diameter
- OTA Masses (650 kg)
- LEO-to-L2 Acceleration (0.26 m/s^2)

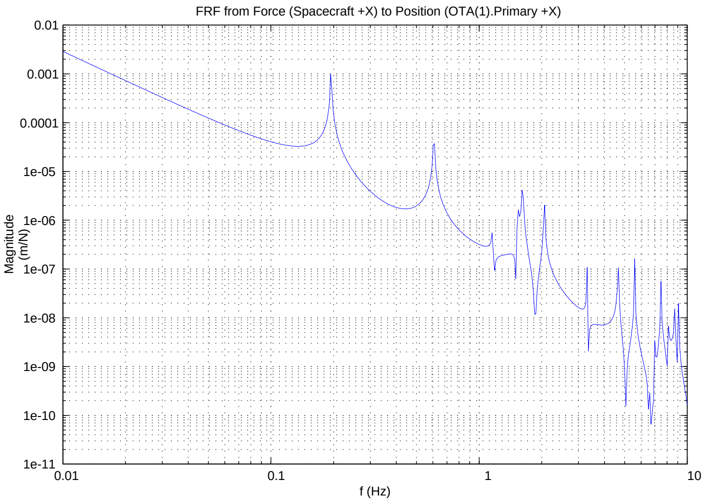


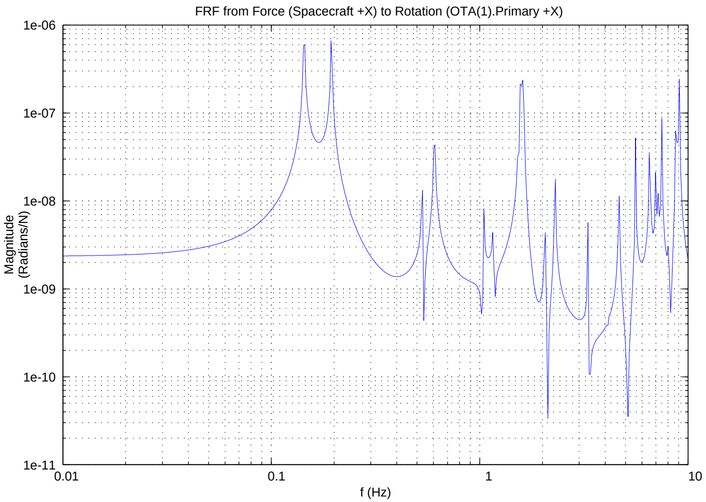
Results of FEM Analysis

- Lowest Truss Vibration Mode
  - 0.14 Hz
- Truss mass
  - 966 kg (of 9100 kg total mass)
- Future Design Considerations
  - LEO-to-L2 boost loads drive buckling stiffness
    - Increases lowest vibration mode above minimum requirement
  - Current design considers uniform truss member properties
    - Would save mass by optimizing distribution
      - Largest members near Spacecraft on compression side
      - Design diagonals for shear rigidity
    - Possible save mass by adopting square truss crossection

Bode Plots of LTI Model

- Left: (X Force to OTA-1 Primary X Displacement)
- Right: (X Force to OTA-1 Primary X Rotation)
- LTI Model Properties:
- 3 Inputs [3 DOF (x,y,z) forces at Spacecraft]
- 90 Outputs [6 DOF Displacements and Rotations]
    - Spacecraft node, 7 OTA PRI mirror nodes, 7 OTA SEC nodes
- 50 Modes [6 rigid body modes, 44 flexible modes]
    - 0.14 Hz to 31 Hz





Disturbance Mitigation

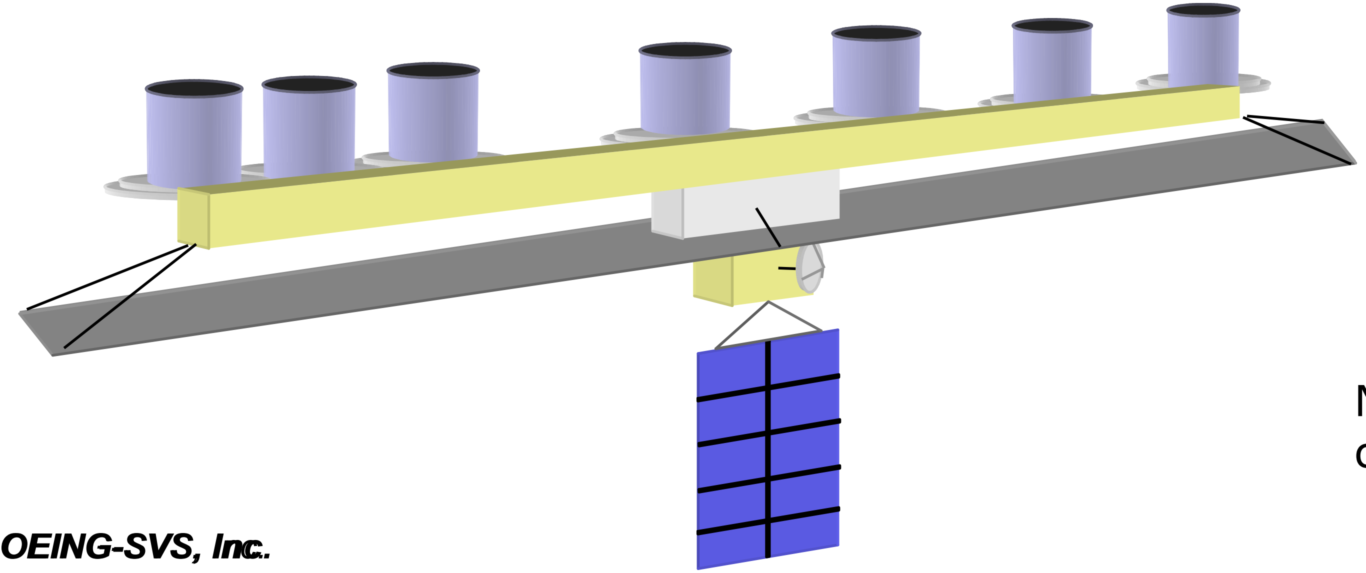
- Conservative approach to structural design → small disturbance impacts expected
- Deformations expected to be small, ~few waves worst-case
  - Simulation confirms < 1 wave in science ops mode [outer OTAs, RW active]
  - LOS pointing & cophasing loops could run at >100 Hz CLBW
    - Expect to need only ~10Hz
- Several options for disturbance isolation
  - Active and passive isolation of OTAs and/or RWs can greatly reduce the disturbance amplitude. The trade may be:
    - Increased relative motion of OTAs may require active compensation.
    - Isolation of RWs may increase attitude control complexity.
  - Active and/or passive damping of boom may also greatly reduce disturbance amplitude.
    - Flight qualified viscoelastic materials exist
    - Smart structure technology has been flight qualified and is well characterized
- Truss configuration of optical boom lends itself to very efficient implementation of advanced composite members with high stiffness, longitudinal orientation.
- This is a design issue but not a technology limiter

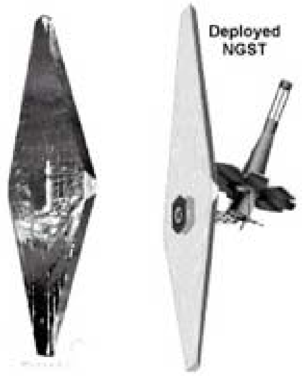
Wavelength(s) of operation and observatory operational temperature

- Initial concept was 5-15μm
- Exhibit II recommends 7-17μm minimum, 3-23μm goal
- We used the SWG Biomarker group report (May 2001) for additional guidance:
  - Biomarker group report recommends 8-20μm minimum, 8-20μm+ (?) goal
    - NRLA can work beyond 15μm with appropriate thermal designs
    - Performance analysis used 7-17μm; coverage 7-20 OK
    - Could be stretched beyond 20μm; detectors good to >25μm
    - Issue would be thermal IR from optics & structure
  - Working temperatures: OTAs/truss 100K, Detectors 10K,
    - Coronagraph and Instrument enclosure 40K

1.5.8 Thermal design concepts

- Thermal shield size is: 22 x 122 m
- Based on NGST design (6 layer); may require only 4 layers required due to temp.=70K (effective emissivity 0.02)
- Other thermal: detector assembly; probably special design, separate radiator





NGST sunshield concept

1.5.7 Requirements on cryogenic components

- Mechanisms
  - Tip-tilt mirrors (FSMs) at OTA and optics bay input
- Actuators
  - DLs (FDL) inside the optics bay
    - CDL portion is static
  - De-densifier active mirrors for piston control (in optics bay)
- Optical elements
  - OTAs, steering & fold mirrors, densifiers
- Opto-mechanical subsystems
  - Coronagraph a key system
  - Tolerances will be tight and active thermal control probably required
    - Radial gradient allowable: 1K
    - Longitudinal gradient allowable: 0.5K

NRLA Cryogenic Mechanisms

Type	Where	No.	Usage	Stroke	Res.	CLBW	Temp
FSM	OTA	7 **	LOS steering 2axis	60 μrad	<10nrad	>20Hz	100K
FSM	OB	7 **	LOS FSM2 2axis	60 μrad	<10nrad	>20Hz	100K
Piezo	OB	7 **	FDL	+/-2 mm	25nm	>100Hz	100K
Piezo	OB	7 **	Phase Modulator	+/- 0.1mm	10nm	>1kHz	100K
Rotating Filter wh.	OB	2	Phase Mask & Spectral Filter wheel	8 pos.	N/A	N/A	<100K

- ** = 1 per beamline

1.5.6 Molecular and particulate contamination effects on optical and thermal surfaces

- Combustion products from attitude control and station-keeping systems
  - MMH byproducts the largest culprit
  - Water and N_2 the largest byproducts
- Outgassing of materials
  - Many potential sources, but for the critical optical parts, thermal shield probably largest; expected loss is ~1% TML; worst-case volatiles deposition < 10nm life of mission at OTA Primary
  - Some degradation of thermal shields and solar cells probable; available data indicates small (few %) changes over mission life
- Ambient materials
  - Assembly in LEO probably largest driver here; sources from NRLA itself plus the assembly hardware, astronauts/robots, and associated systems
- Proposed mitigation techniques
  - Molecular films: expect principally H20 (N2 won't stick) but more complex organics possible
  - Thorough cleaning after assembly, before boost to L2; covers for prop to L2
  - Warming of optics periodically (heaters plus some sun exposure)
  - Caution re: particulates – won't necessarily deposit with or come off with molecular films, and low mass maybe not detectable with quartz crystal microbalance (QCM)
  - Need on-telescope scatter monitors and possible CO2 snow system
  - Area for technology investigation

Current technologies for suppressing and managing contamination

- Optical surface cleaning methods:
  - Boil-off (warming): safest; won't necessarily remove everything
  - Beam cleaning (e.g., ion beams) – some research done years ago (c. 1990) but still unproven; risks (energy of particles)
  - CO2 snow: used on ground; no space demo yet
- More data is needed (flight experiments) on very-near-angle scatter from contaminants (as well as from mirror surface)
- As a minimum, scatter instrumentation should be included on any TPF mission
  - QCM a useful diagnostic but not a direct measurement of effects
  - Small BRDF monitors can be built into any telescope

1.5.9 Options for integration-and-test and pre-launch performance verification

- Integration &Test Options:
  - Deploy at L2
    - requires ground testing of system
    - requires deployment mechanisms/hardware
  - Assemble at L2
    - Humans and/or robots
    - A mix of assembly+deployment is possible
  - Deploy in Earth orbit, Boost to L2
    - Full or partial test/evaluation on orbit
  - Assemble in Earth orbit, Boost to L2
    - Full or partial test/ evaluation on orbit
    - Humans and/or robots
    - Mixed assembly/deployment is possible

I&T impacts: Comparison

If we compare to deployment at L2, then:

- Deployment at LEO
  - Similar launched mass/volume and launch strategy
  - Has potential for repair/servicing although not needed, nominally
  - Will allow for reduction in ground test facilities, some testing can be in LEO
  - Has some design impact since the deployed system must boost to L2
- Assembly at LEO
  - Has lower launched mass/volume for NRLA system (no deployment hardware)
  - Possibly outweighed by additional launches for humans/robots for assembly
  - Has largest flexibility in assembly & servicing options since this is planned in
  - Will allow for reduction in ground test facilities, some testing can be in LEO
  - Has some design impact since deployed system must boost to L2
- Assembly at L2
  - Has lower launched mass/volume for NRLA system (no deployment hardware)
    - Possibly outweighed by additional launches for human/robots for assembly
    - Note Humans at L2 likely not feasible in planned TPF timeframe
  - Has some flexibility in servicing options
  - Will allow for reduction in ground test facilities, some testing can be on station
  - Has some design impact (I.e., needs some assembly-related features designed in)
  - Could have large technology impact
    - Either new manned vehicles or remote autonomous servicers (or both)

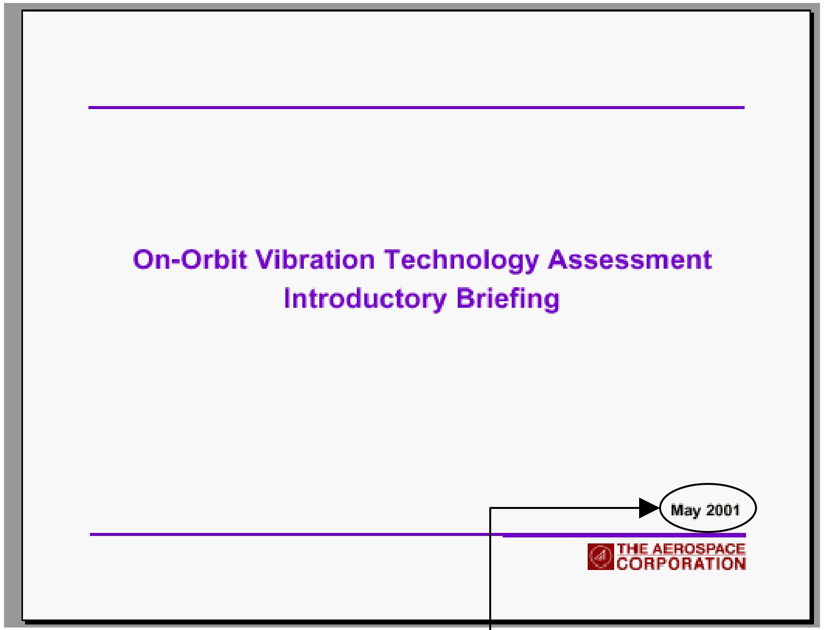
Integration & Test -- Approach

- Deployment at L2 (a la NGST) is risky:
  - Deployment may not work
  - If deployment works, system may not perform
    - Ground tests of integrated system of this scale are not indicative of performance on orbit
  - Ground facilities to do these tests don't currently exist, will be very expensive to
  - develop, and will not reproduce the environment adequately
- Our approach:
  - Ground test systems functionally, and performance as individual elements
    - e.g., test the OTAs individually, optics bay, coronagraph
  - Ground test with simulated conditions where this is realistic in scale
    - e.g., test the optics bay for cophasing on the ground but not with 100m baseline
  - Launch the system in pieces and assemble in earth orbit
  - Test the integrated system to some level in earth orbit:
    - Find out that it is functional
    - Fix anything that doesn't work
    - May be possible to do limited performance testing in LEO
      - Not a full-up science evaluation
  - Boost the system to L2
  - Commission the system at L2: full functional, performance tests, calibration

General Advantages of Space Assembly and Testing

- Space assembly and testing will be a significant factor in future astronomical missions:
  - Exploits the adaptability of optics and structures in future large optics systems
  - Reduces reliance on large environmental chambers
  - Avoid the costly development of high performance star simulators
  - Avoids testing in 1G
- Can provide repairable, maintainable, scalable, upgradeable systems
- Avoids limitations of launch vehicles to achieve scalable solutions
  - Smaller launchers may become candidates if assembly is considered
- Recognize that perfection in the system is not possible, desirable or worth the expense, UNTIL IT GETS TO ITS OPERATIONAL ENVIRONMENT
- Numerous recent studies have found significant benefits from space assembly and testing, done properly
  - 1G functional testing of components suitable for such testing
  - Pre-launch system performance verification by integrated analysis and subsystem performance margins
  - 1G assembly of the entire observatory to prove fit and integration
  - Disassembly for flight
  - Assembly on orbit
  - On-orbit functional testing of the observatory
  - On-orbit performance testing, if possible in LEO

Others are Beginning to Address the 'On Orbit' Testing Approach



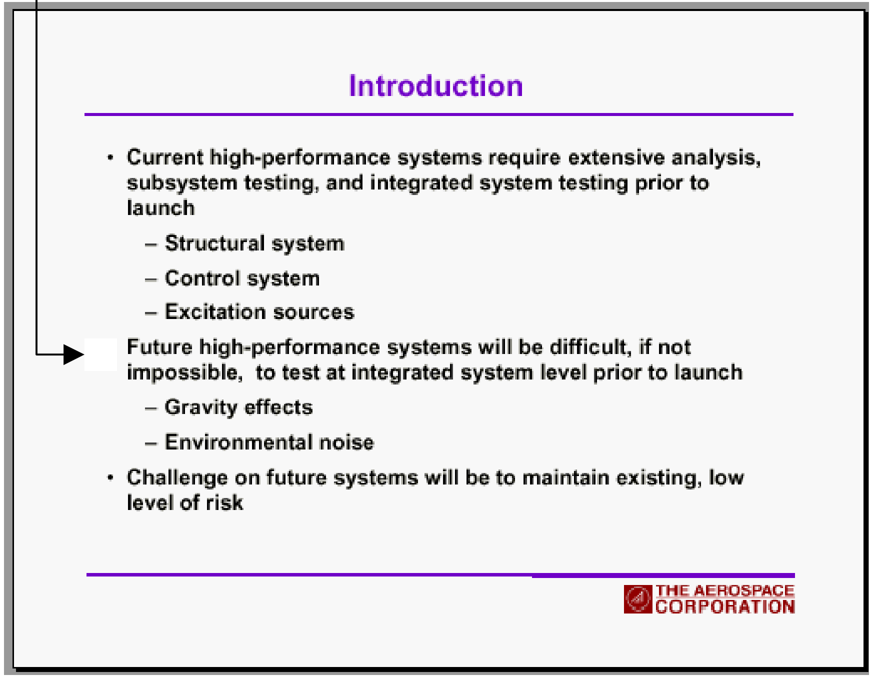
On-Orbit Vibration Technology Assessment
Introductory Briefing

May 2001

THE AEROSPACE CORPORATION

Very recent activity

Critical to optics as well



Introduction

- Current high-performance systems require extensive analysis, subsystem testing, and integrated system testing prior to launch
  - Structural system
  - Control system
  - Excitation sources
- Future high-performance systems will be difficult, if not impossible, to test at integrated system level prior to launch
  - Gravity effects
  - Environmental noise
- Challenge on future systems will be to maintain existing, low level of risk

THE AEROSPACE CORPORATION

On-orbit I&T: Impacts & Risks

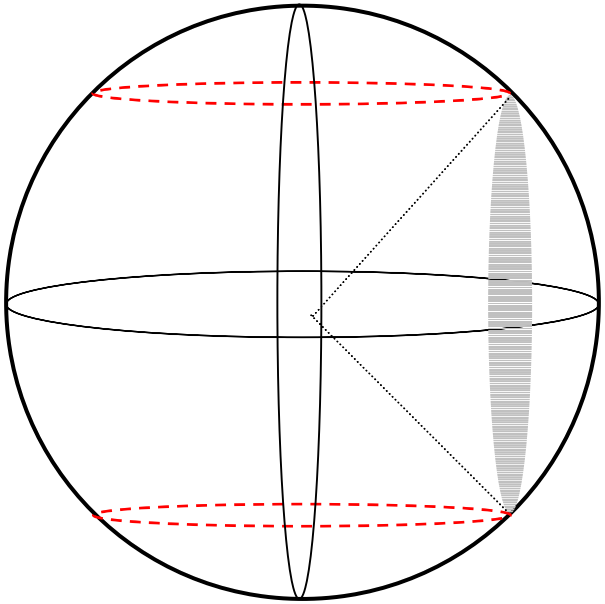
- Some Impacts for Assembly in LEO, boost to L2
  - Design Impacts
    - Structural mods needed to allow acceleration loads for boost to L2 (included in design concept)
    - Environmental risks (debris, O+, contamination, radiation, etc.)
    - Optical Systems need replaceable covers
      - Uncover for on-orbit testing
      - Replace before boost to L2
  - Operations
    - Current assembly and integration of ISS should provide a large experience base for human on-orbit assembly tasks
    - But, does not involve precision optics, delay lines, etc.
    - Implications for astronaut and robotic tooling and servicing aids
- Assembly of large optical systems in space is an acknowledged need for future systems
  - Will provide heritage to expected generation-beyond systems (e.g., *PI*)

1.5.10 NRLA Orbit Trades: L2 Selected

Mission & Spacecraft Issues	Earth-Trailing (drift-away)	L2 Lagrange Point	1x5 AU ecliptic elliptic
Orbit Heritage	SIRTF	SOHO, IEEE-3, WIND, NGST	Not previously used
Zodiacal Dust / Aperture Size	Higher input from zodiacal dust forces larger apertures	Higher input from zodiacal dust forces larger apertures	Lower input from Zodiacal dust
Launch Vehicle Selection	Multiple vehicles available (C3=0.4 km^2/s^2)	Lowest DV requirement – multiple vehicles available (C3=0.69 km^2/s^2)	Restricted vehicles selection (C3=75 km^2/s^2)
Operational Orbit Insertion	All elements of observatory at one time	May be inserted in stages	All elements of observatory at one time
Power	Near-constant solar input – simplifies power system design	Near-constant solar input – simplifies power system design	S/C design driver: EOL array size huge; new power system needed
RF Comm	Changing range during mission life. Requires DSN (34m, 70m ant.)	Constant range. <34m commercial ground antenna possible	Changing range during mission life. Requires DSN (34m, 70m ant.)

NRLA Sky Coverage

- Due to rotation about LOS, allowable sun exclusion angle is symmetric with respect to LOS
- Thermal shield configuration determined solar exclusion angle
- Possible shield configurations
  - Flat plane (rectangular)
  - Flat w/side panels
- Side panels, if any, will determine whether viewing to heliocentric orbit poles possible
  - If no side panels, poles excluded, hence
    - Never achieve full sky coverage
  - Side panels produce change in center of pressure (solar torque) as system rotates
    - Omitted in current design concept
- Flat shield is simplest choice
  - 122 x 22m gives 45 deg. from antisunward line, instantaneous coverage
  - 71% of total sky available during orbit (15% instantaneous)
  - 90 day observation period over most of available sky (revisit 270 days)
  - Coverage could be increased to ~ 60 deg. (2x heavier shield)

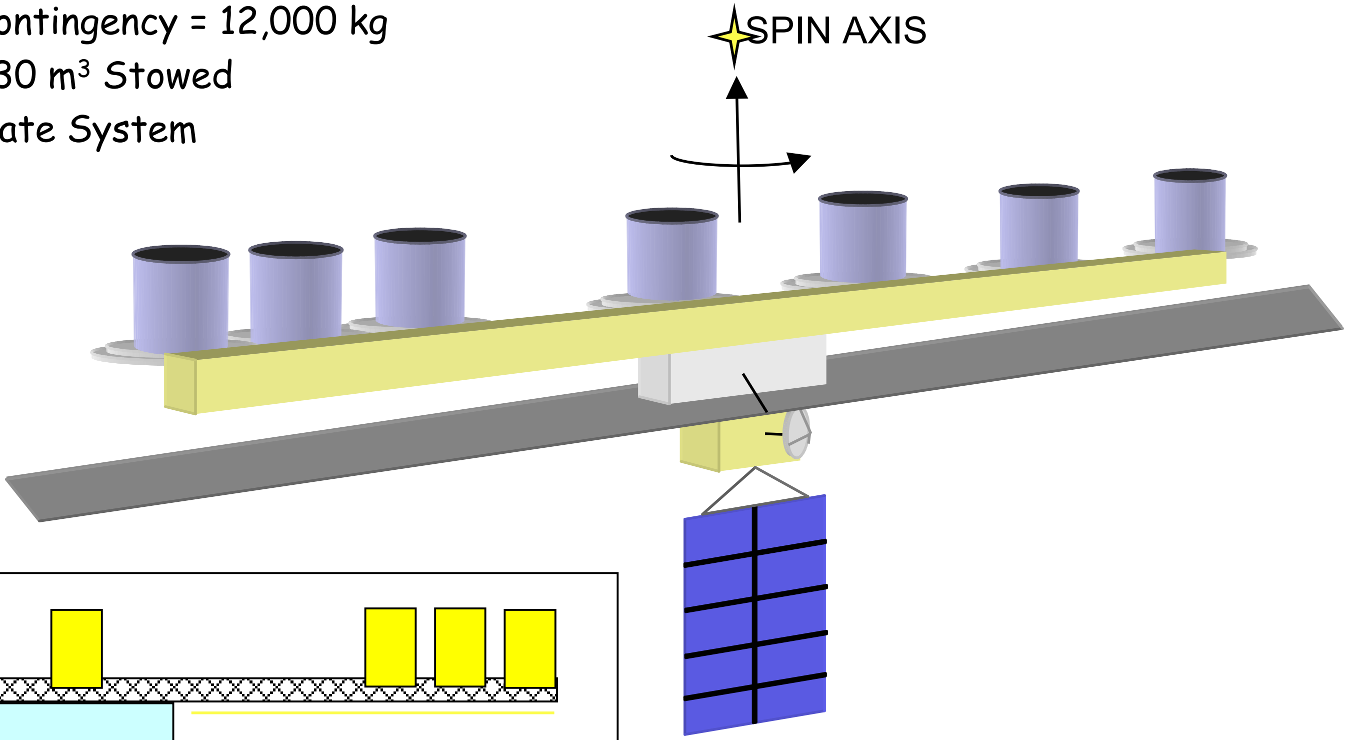


1.5.13 Operations scenario

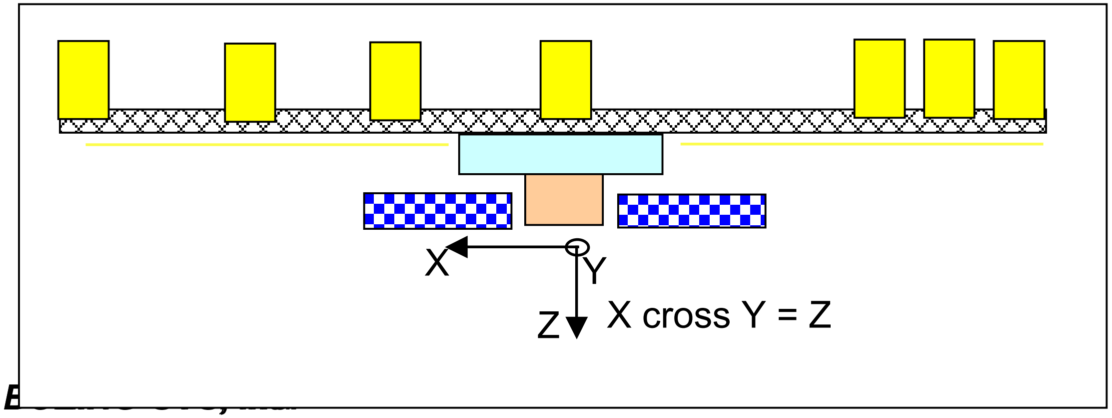
- Spin-up and repoint using RWs
  - Could also be done with thrusters; RWs chosen for baseline concept
  - Thrusters for desaturation, < 100kg net mass over mission life
  - Typical repointing angle (survey mode) ~10 degrees
- Duration of observation of each star depends on mode:
  - Initial survey: 2.5 hrs (Continuum at 8.67μm, Filtered Spectroscopy)
    - Using a dispersive spectrometer → multiple bands in parallel
  - Higher R, Higher SNR bands:
    - Observation times < 50hrs total (4 sequential sets of observations, 4 bands) out to d= 20pc, l < 15 μm
- Sampling the celestial sphere:
  - Do 2-3 observations per object in initial sequence
    - Small time loss due to filter switching
    - Net 8 hrs per object (Cf. observing time budget)
    - Data is processed on ground for initial assessment
      - More detailed assessment, if desired, should be soon due to time window for observations
      - Initial ground reprocessing should focus on detection and selection for revisits

NRLA Space Segment

- Point Design
  - (7 Three-Meter Telescopes)
  - Mass with contingency = 12,000 kg
  - Volume = ~130 m^3 Stowed
  - S/C Coordinate System



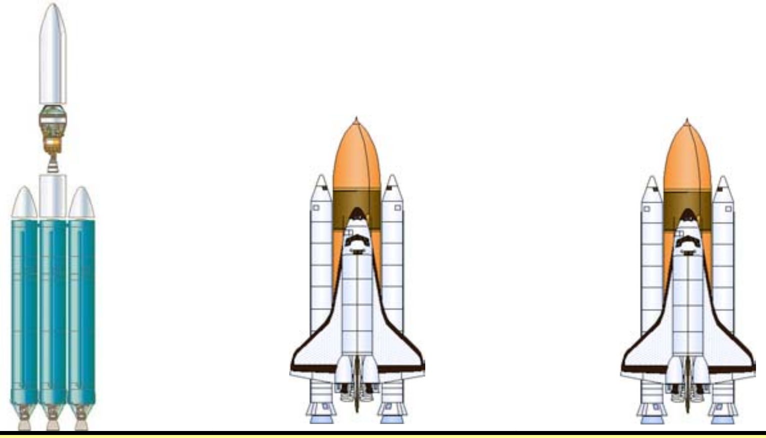
Not to scale



1.5.11 NRLA: Launch Strategy

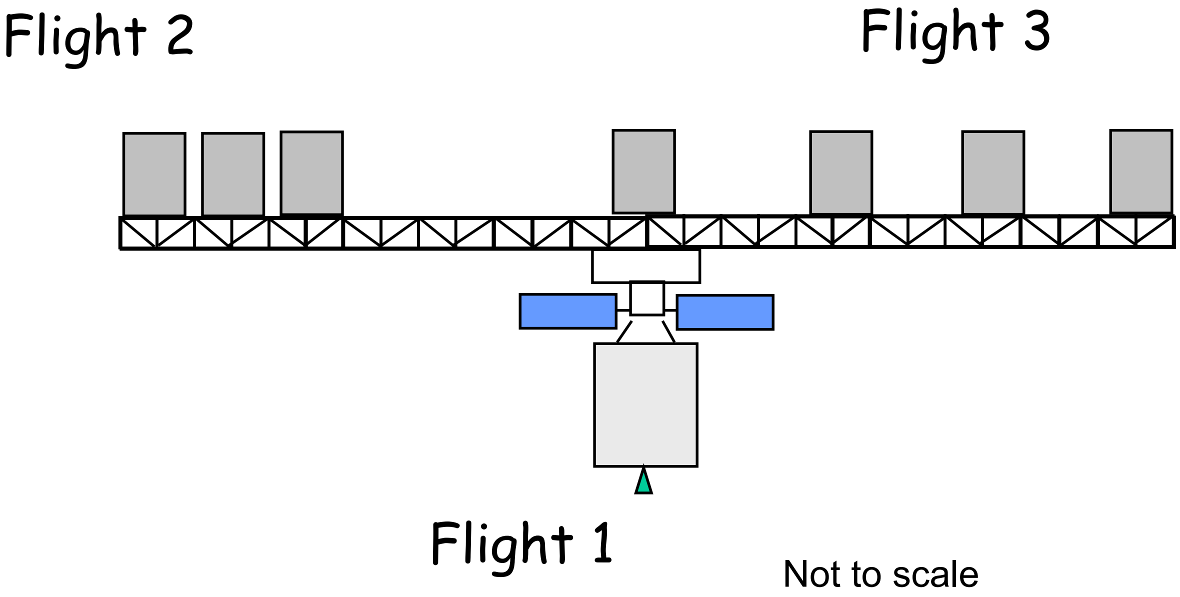
- LEO Parking orbit assumed
- Launch vehicle highly dependant on
  - OTA mass and volume
  - Number and type of propulsion system
  - LEO orbit altitude/inclination
  - Required presence of humans in close proximity
- Volume constraints preclude use of single launch vehicle
- Distributed Launches
- Components not requiring assembly launched first
- Attitude and Orbit Control on first launch
- Analogous to ISS assembly
- Manned Presence Required

NRLA Launch (cont'd)



TPF LAUNCH	FLIGHT 1	FLIGHT 2	FLIGHT 3
Vehicle	Delta IV-H	STS	STS
Components	Bus, Optics Bay, Upper Stage	3 OTAs, 1/2 boom	4 OTAs, 1/2 boom
Mass to Orbit, kg	18118	2350	3050
Stowed Volume, m^3	83	54	71
Assembly scheme	initial deployment	manned EVA	manned EVA

1.5.12 Deployment strategy and assembly sequence

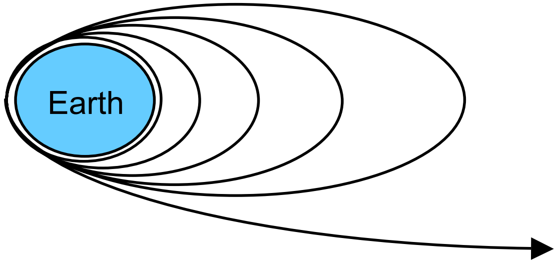


Time to Assemble 1/2 Boom
- ~30 struts per hour
- ~16 hours (working time) of EVA for 1/2 boom

Low Earth Orbit

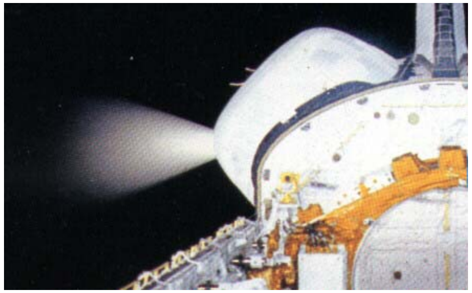
- Assembly or Deployment in LEO (425 km, 28.5 deg, < 6 Month Duration)
- Issues
  - Gravity Gradient Attitude
    - Driver for angular momentum storage (9700 N-m-s)
  - Power
    - 35 minute eclipses every 93 minutes
    - Driver for battery systems
  - Propulsion
    - Depending on time in LEO, drag make-up may be necessary
    - Debris avoidance maneuvers (statistically 1 close-call, <1 km range)
  - Environment
    - Small particle debris
    - Atomic oxygen

Leaving low earth orbit

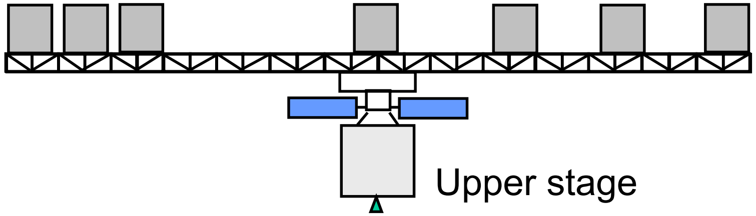


- Chemical propulsion with multiple burns
- Assuming 30 burns
  - Maximum acceleration = 0.26m/s^2 (0.027 g's)
  - Thrust required = 3150 N (708 lb)
  - Next-to-last burn raises apogee beyond moon's orbit
    - Apogee = 450,000 km
    - Possibility of lunar flyby to eliminate last burn (save ~150 m/s)
- Disposable "upper stage"
  - Based on centaur-g
  - Smaller LOX/LH2 engine based on rocketdyne RM-1500H
  - Jettison ΔV propulsion system after earth departure
  - Retain smaller onboard ΔV and ACS propulsion system

Propellant mass, LH2/LOX = 14,000 kg



Point of reference:
The primary RCS thrusters on the Space shuttle are 3870 N each



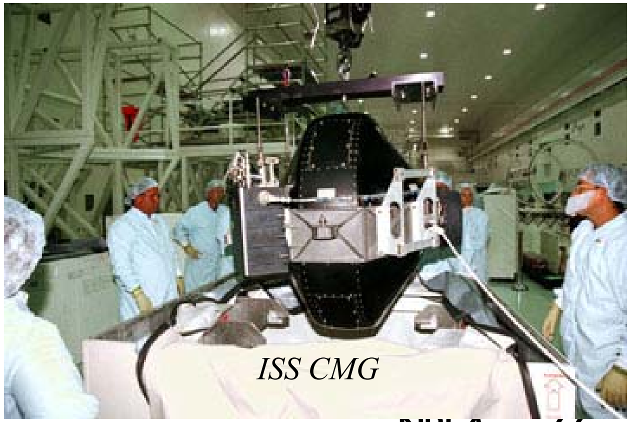
Upper stage

Cruise and arrival at L2

- Time-of-flight (cruise to L2)
  - Approximately 103 days after final burn
- No eclipses
- Regular communications opportunities
- Delta V of only 5m/s for HALO insertion
- Can be performed with small chemical or electrical thrusters
- Deployment of thermal parasol after L2 insertion
- 5 m/s insertion also implies 5 m/s to get out of HALO
  - ~1200 m2 of thermal shield acts as solar sail
  - Potential 0.1 m/s per year ∆V from radiation and solar wind

Repointing Operations

- 10 degree repoint in 5 hours (5 hr rotation about Z axis)
  - Momentum to be imparted and later removed: 80.4 n-m-s
  - Substantial moment arm available for thrusters
  - Propellant consumed ~0.01 kg (1-second burn time)
- 10-degree repoint in 5 hours (5 hr rotation about X axis)
  - Momentum to be imparted and later removed: 0.7 n-m-s
  - 1-m thruster moment arm
  - Propellant consumed ~ 0.005 kg (0.4-second burn time)
- Total angular momentum of system while spinning
  - 2900 n-m-s
- Wheel option (control moment gyros)
  - ISS control moment gyros can store 4700 n-m-s
  - Propulsion needed for wheel de-saturation
  - Repointing not a driver for wheel size



ISS CMG

Downlinking Data

- Assuming x-band, DSN compatible
- Options:
  - S/C 1-m high gain antenna on 2-DOF gimbal
    - 8-hour downlink session per week (2 mbps data rate)
    - 40-W RF output gives substantial link margins on 34-m DSN subnet
    - 40-W RF output gives +6 db margin with 13-m commercial antenna (lower operational cost)
  - 2+ omnidirectional antennas (no high gain parabolic antenna)
    - 8-hour downlink session per day (35 kbps data rate)
    - 350-W RF output gives 3.3 db margin with 13-m commercial antenna
    - Possible, but would require higher capacity bus power system and larger arrays (issue - no commercial antennas currently support DSN CCSDS)
- Both cases: command uplink/ spacecraft downlink via omni antenna

Mass Budget

- High level mass budget

Major Components	Mass	#		subtotal
OTA	700 kg	7	=	4900 kg
Boom	500 kg	1	=	500 kg
Optics Bay	1100 kg	1	=	1100 kg
Thermal Shield	900 kg	1	=	900 kg
Bus **	2500 kg	1	=	2500 kg
			TOTAL	9900 kg

** based on upgraded STAR-2 bus

- Most calculations Use total Plus 20% Allocated Margin (12,000 kg)
- Spacecraft MOI About Z-axis = 8.3×10^6 kg-m^2

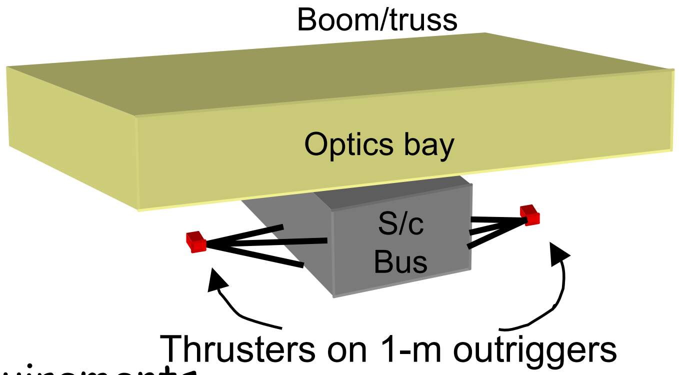
Power Budget

- Bus power sizing drivers
  - Amplifiers for RF communications (40-W)
  - Propulsion line heaters

Major Components	Power (total), W
OTA	1085
Boom	0
Optics Bay	500
Thermal Shields	0
Bus	1000
TOTAL	2585

- Assuming 28% efficient cells, 85% packing factor, 5 year radiation degradation numbers
  - Array area required = 10.0 m^2 (with 30% margin)
  - Comparable to current large geos

On-station propulsion



- (Excluding The major delta-v burn)
- L2 insertion, 5m/s
  - 87 kg (nitrogen)
  - 32 kg (hydrazine)
  - 8 kg (hydrogen resistojet)
- L2 maintenance
  - About 10% of the insertion propulsion requirements
- Thruster option for 350 objects - thrusters on boom
  - 310 kg (nitrogen)
  - 113 kg (hydrazine)
  - 27 kg (hydrogen resistojet)
- Wheel option - thrusters on spacecraft bus
  - Thrusters needed for momentum unloading
  - Significantly lower propellant needed

1.7 NRLA Cost Estimate

- Total life-cycle cost for TPF-NRLA: $2.83 billion (2002 dollars)

TPF - NRLA	COST	%
Space Segment	$ 517 M	18.3%
Launch Segment**	$ 2.0 B	70.7%
Ground Segment	$ 130 M	4.6 %
Mission Ops & Data Analysis	$ 167 M	5.9 %
Education & Public Outreach	$ 14 M	0.5 %
TOTAL	**$ 2.83 B**	**100 %**

** =Note: full cost accounting for STS flights

NRLA Risk Assessment

	Performance	Cost	Schedule
– I&T Methodology for Optical Systems on-orbit is very immature • Sequencing, methods/tools, functions, & timelines need to be developed	X	X	X
– NRLA Design Concept can undergo further optimization • To be expected at this stage of development • Neither a cost/schedule driver if this is done early • Plus, planet detection/characterization requirements still evolving	X		
– Some Technology items unproven, no flight hardware • Processes, suppliers must be developed; Flight Eval./Qual. needed • To be addressed through Technology Development program • Also, dependent on some technology insertion from other programs	X	X	X
– NRLA System is complex: potential reliability risk • Can be mitigated with proper design and testing • Neither a cost/schedule driver if addressed early in design	X		

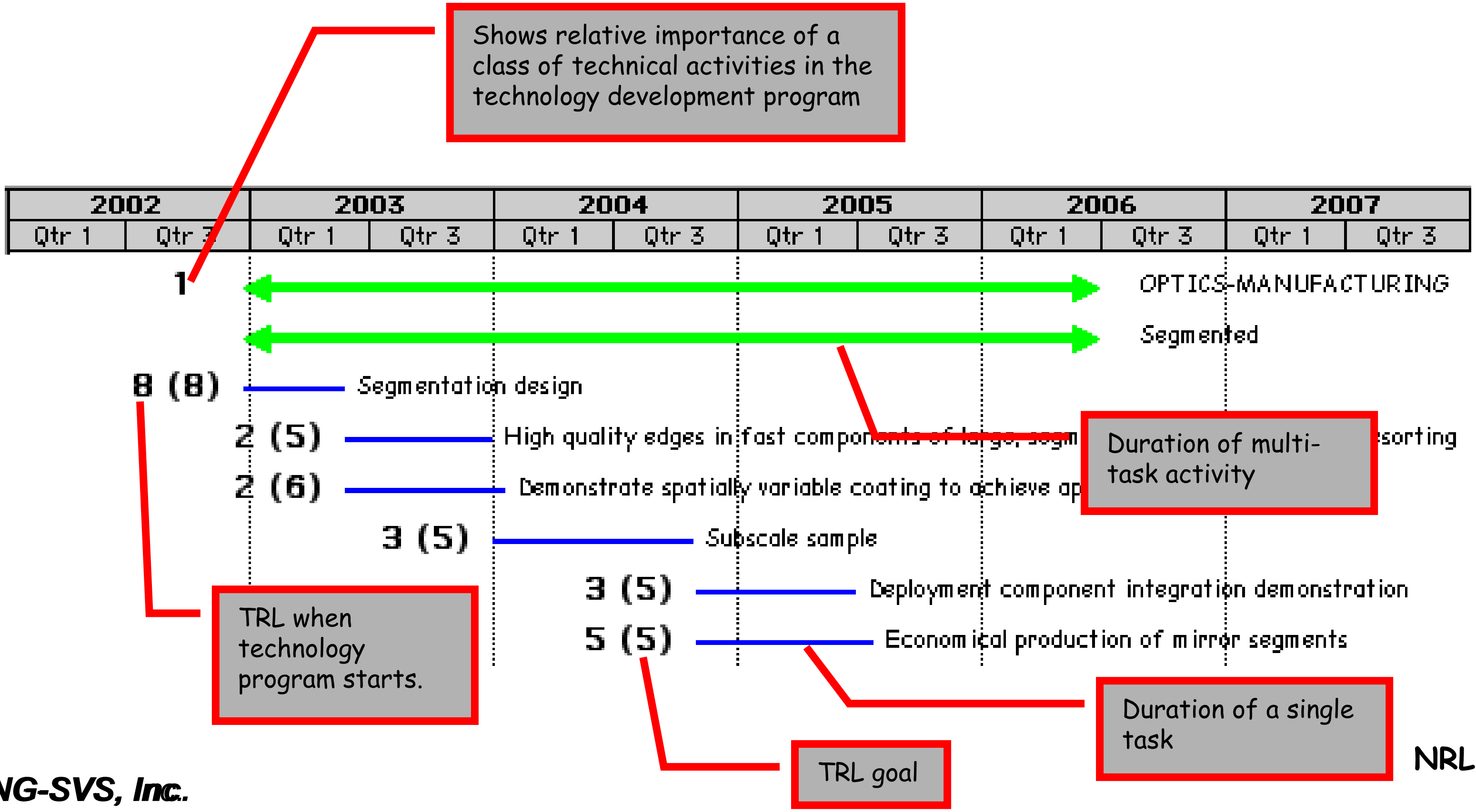
1.8.2 A roadmap for technology development

1.8.2 A roadmap for technology development

- The following charts illustrate roadmaps, TRL levels and timelines
- Technical topics were chosen using the following criteria
  - We do not address topics that are already under development throughout the community
  - No attention to topics for which there is already substantial technical maturity
  - Focus on topics that enable the ASA mission
- Dependencies are not shown to keep the charts clear

1.8.3 Metrics for assessing technology maturity and readiness

- Our roadmap approach uses various metrics
  - NASA TRL in two ways
  - A qualitative measure of importance of the technology advance



Shows relative importance of a class of technical activities in the technology development program

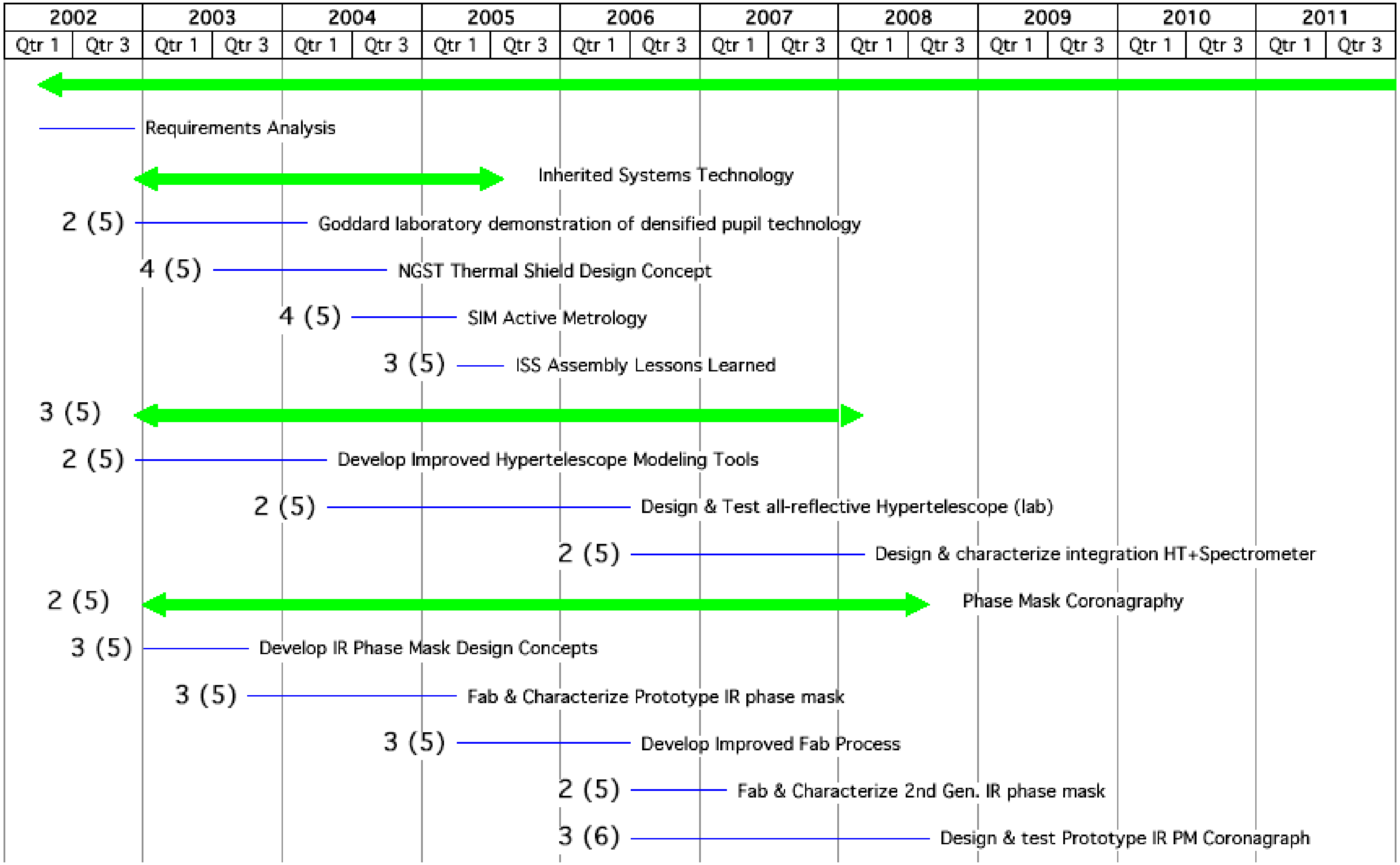
Duration of multi-task activity

TRL when technology program starts.

TRL goal

Duration of a single task

Elements of the technology program (1)



Requirements Analysis

Inherited Systems Technology

2 (5) Goddard laboratory demonstration of densified pupil technology

4 (5) NGST Thermal Shield Design Concept

4 (5) SIM Active Metrology

3 (5) ISS Assembly Lessons Learned

3 (5)

2 (5) Develop Improved Hypertelescope Modeling Tools

2 (5) Design & Test all-reflective Hypertelescope (lab)

2 (5) Design & characterize integration HT+Spectrometer

2 (5) Phase Mask Coronagraphy

3 (5) Develop IR Phase Mask Design Concepts

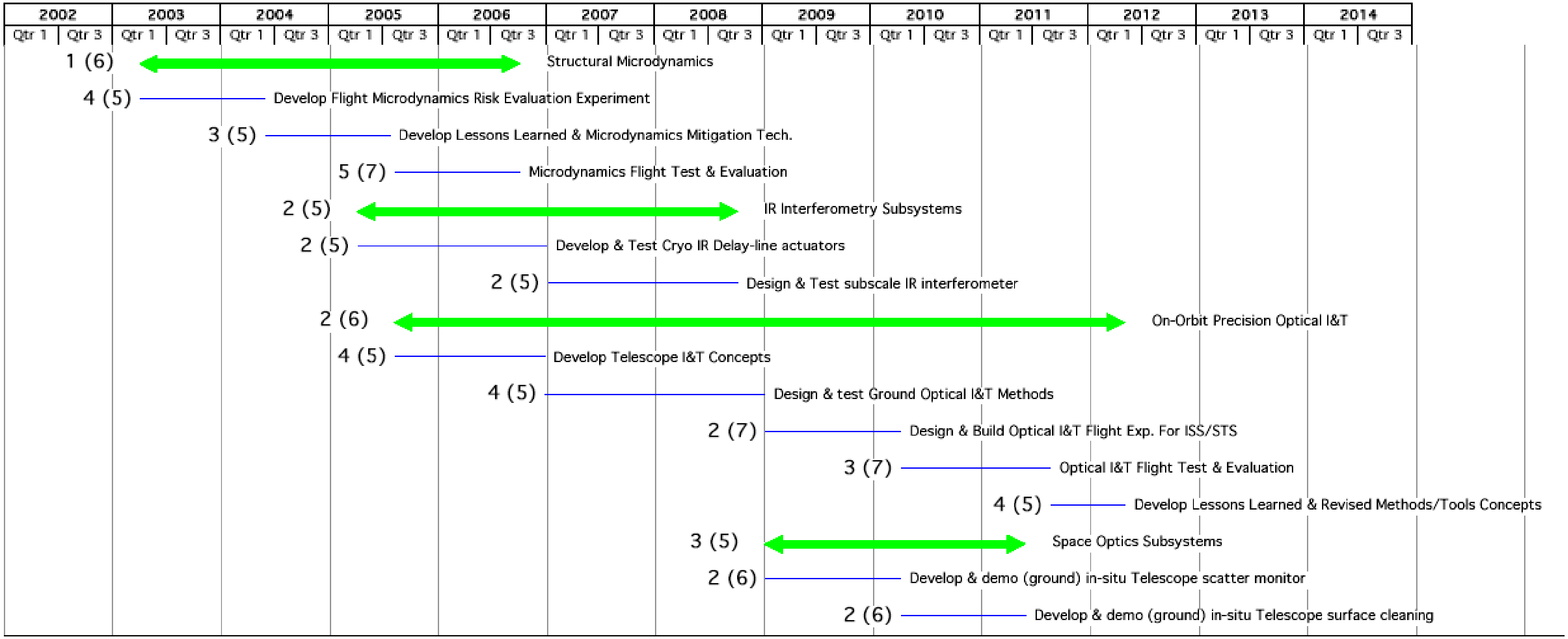
3 (5) Fab & Characterize Prototype IR phase mask

3 (5) Develop Improved Fab Process

2 (5) Fab & Characterize 2nd Gen. IR phase mask

3 (6) Design & test Prototype IR PM Coronagraph

Elements of the technology program (2)



1 (6) Structural Microdynamics

4 (5) Develop Flight Microdynamics Risk Evaluation Experiment

3 (5) Develop Lessons Learned & Microdynamics Mitigation Tech.

5 (7) Microdynamics Flight Test & Evaluation

2 (5) IR Interferometry Subsystems

2 (5) Develop & Test Cryo IR Delay-line actuators

2 (5) Design & Test subscale IR interferometer

2 (6) On-Orbit Precision Optical I&T

4 (5) Develop Telescope I&T Concepts

4 (5) Design & test Ground Optical I&T Methods

2 (7) Design & Build Optical I&T Flight Exp. For ISS/STS

3 (7) Optical I&T Flight Test & Evaluation

4 (5) Develop Lessons Learned & Revised Methods/Tools Concepts

3 (5) Space Optics Subsystems

2 (6) Develop & demo (ground) in-situ Telescope scatter monitor

2 (6) Develop & demo (ground) in-situ Telescope surface cleaning

NRLA Summary

- The NRLA concept has significant potential for planet detection and study, as well as general astrophysics
  - It can perform the TPF mission as we now understand it
- It can be developed using reasonable technology advances
  - Some key items need development, but they are extrapolations of current technology
- It is a scalable concept
  - Flexibility to adapt to changes in TPF programmatic requirements
- It prepares a technology path to free-flyer hypertelescope arrays
  - Only an imaging array can respond to the long-range navigator need for a planet imager