NASA

JPL

Terrestrial Planet Finder Mission

TPF

Terrestrial Planet Finder Interferometer: architecture, mission design and technology development

Curt Henry
Interferometer Systems Manager
June 22, 2004

SPIE Astronomical Telescopes and Instrumentation
Glasgow, Scotland

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Co-Authors

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- Oliver Lay – Chief Architect
- MiMi Aung – Manager of the Formation Flying Technology
- Steve Gunter – Manager of the Interferometry Core Technology
- Serge Dubovitsky – former Chief Architect
- Gary Blackwood – former Interferometer Systems Manager

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Purpose of This Talk

Overview of TPF-I since August 2003

Details elsewhere

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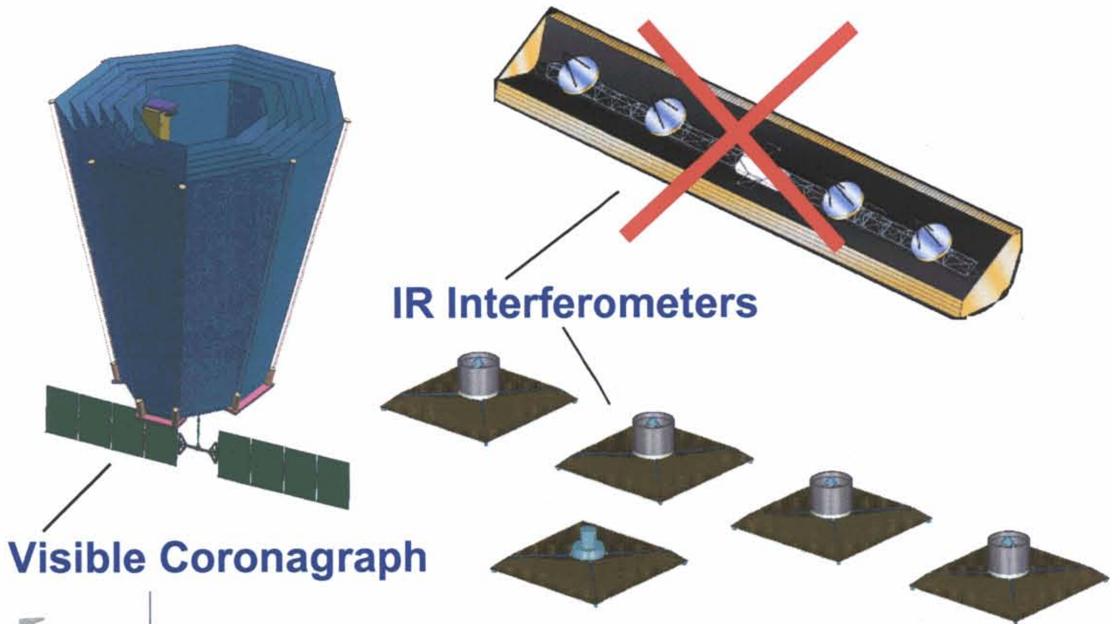

Program:

- Launch a moderate sized coronagraph ~2014
- Launch a formation flying interferometer ~2019
- 5 year mission life, 10 year goal
- Potential collaboration with ESA DARWIN

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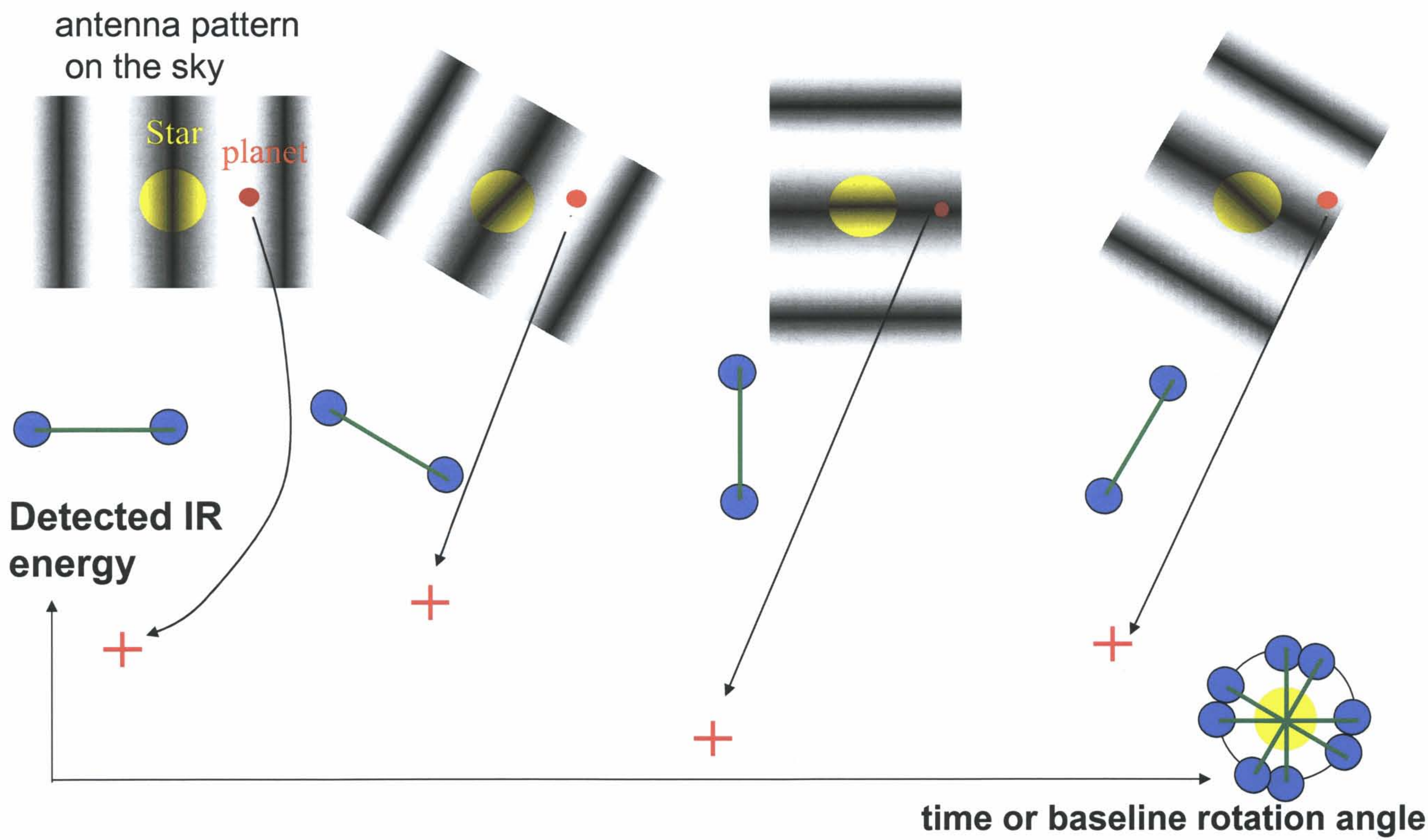
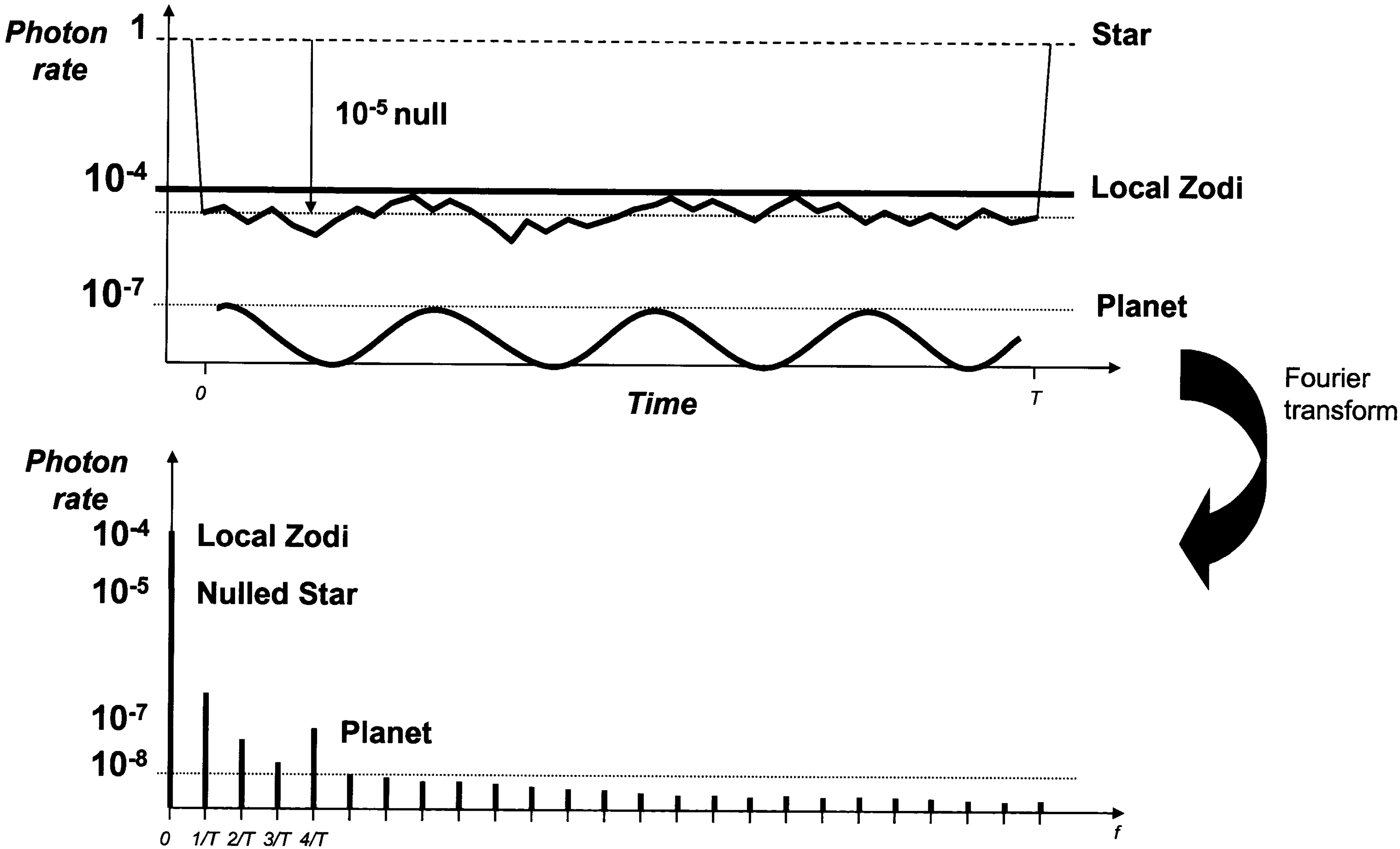
Science:

- **Detection**: Survey a *statistically significant number* of solar type stars for Earth-mass planets (>35 stars or >~150 stars)
- **Habitability:** Make low resolution spectral observations of the brightest planets for signatures of CO_2 and H_2O.
- **Biomarkers:** Make very sensitive, low resolution spectral observations of the most interesting planets, looking for O_2 or O_3 and CH_4
- **Ancillary science:** perform as capability and time allow

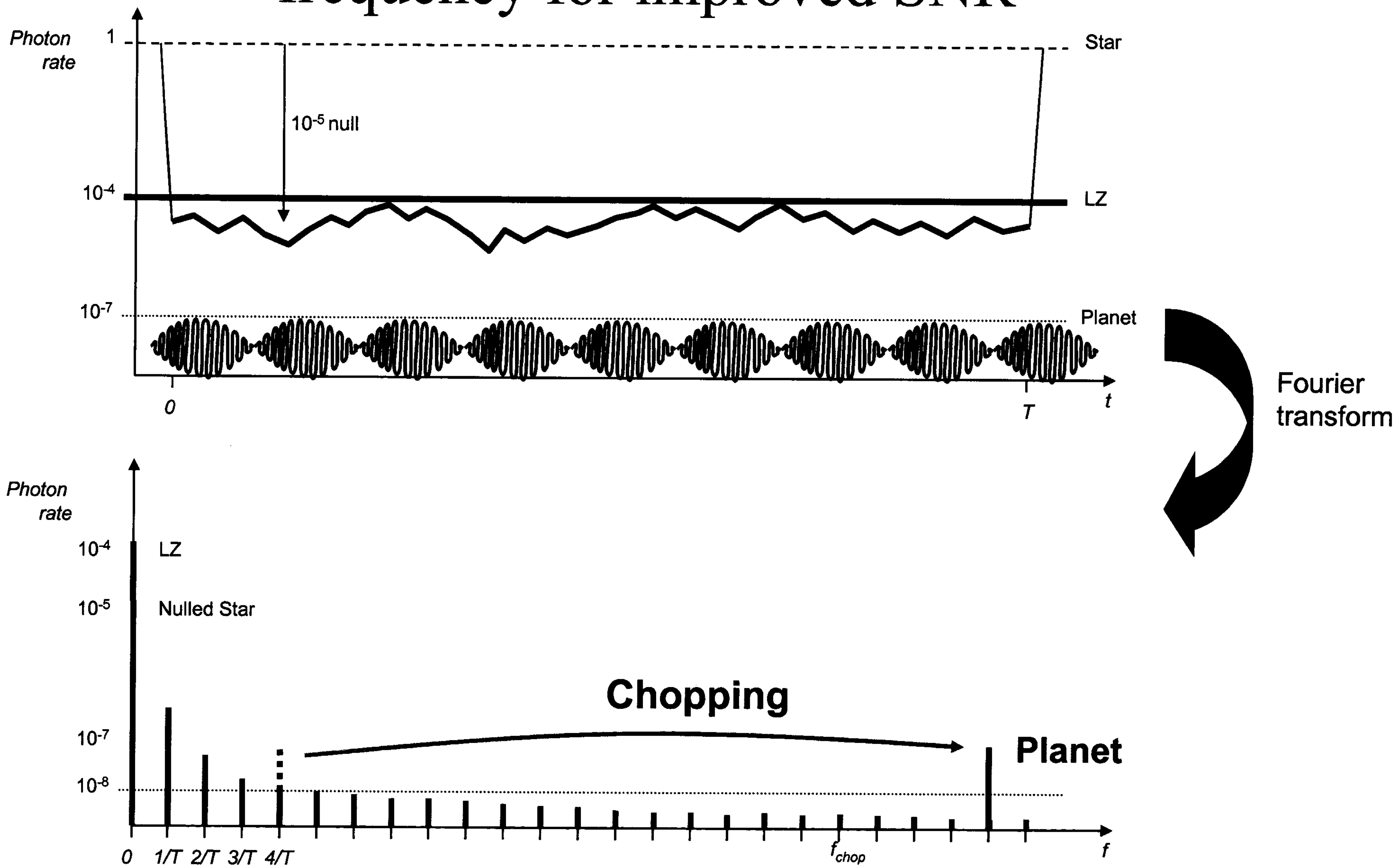
Interferometer Exo-Planet Detection



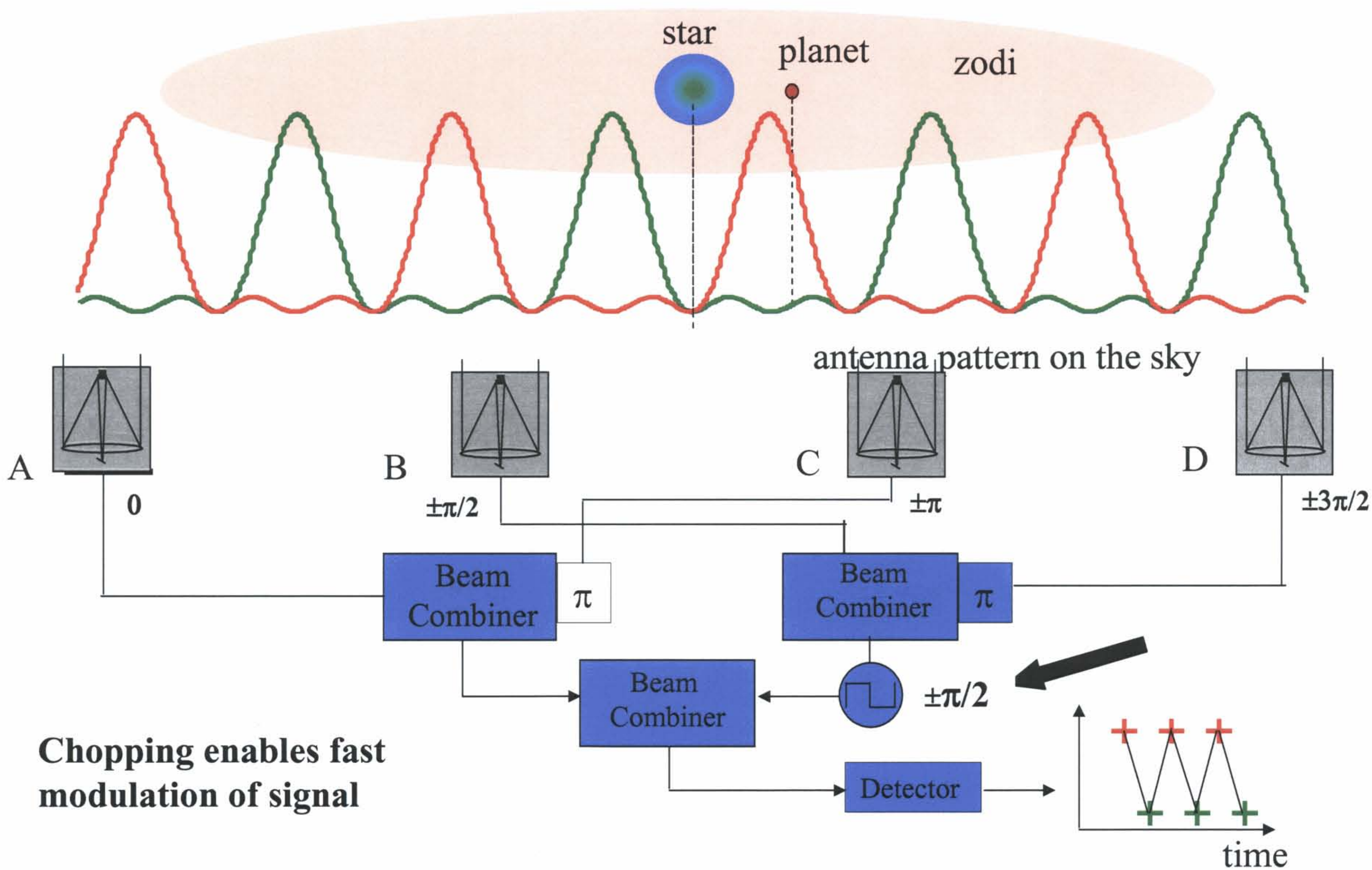
Null depth and null stability



Chopping moves planet signal to higher frequency for improved SNR

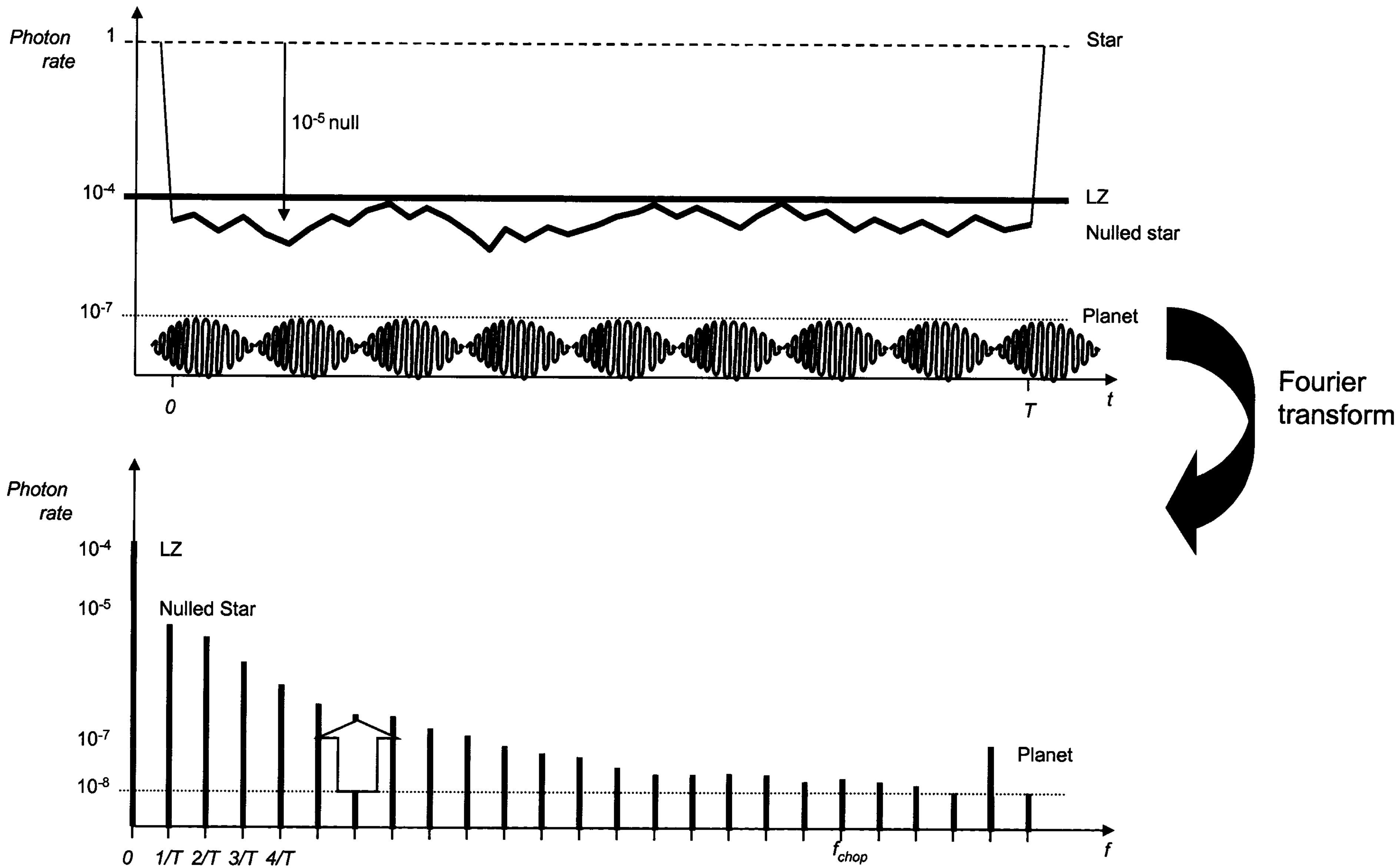


Chopping: a method for background suppression

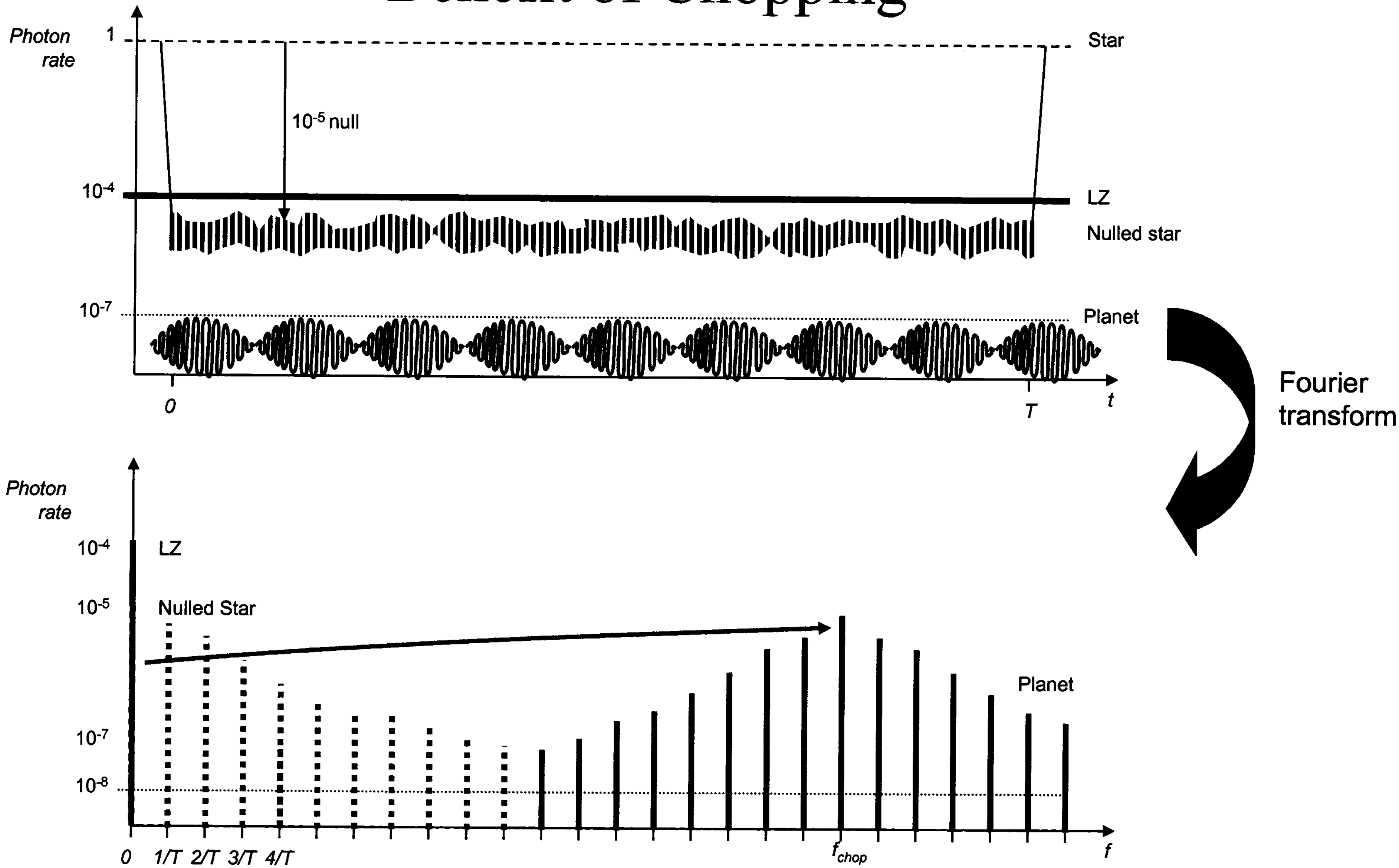


Chopping enables fast modulation of signal

Or greater tolerance to systematic noise



New Bi-linear Errors Reduce the Benefit of Chopping



Chopping Removes Some Errors

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- But is ineffective against the new, dominant, mixed amp-phase terms

~~$\{\delta A_j\}$~~	~~5%~~
→ $\{\delta\phi_j\}$	1%
~~$\{\delta A_j \delta A_k\}$~~	~~20%~~
→ $\{\delta A_j \delta\phi_k\}$	53%
~~$\{\delta\phi_j \delta\phi_k\}$~~	~~20%~~
~~$\{\delta x_j\}$~~	~~1%~~
$\{\delta y_j\}$	0%

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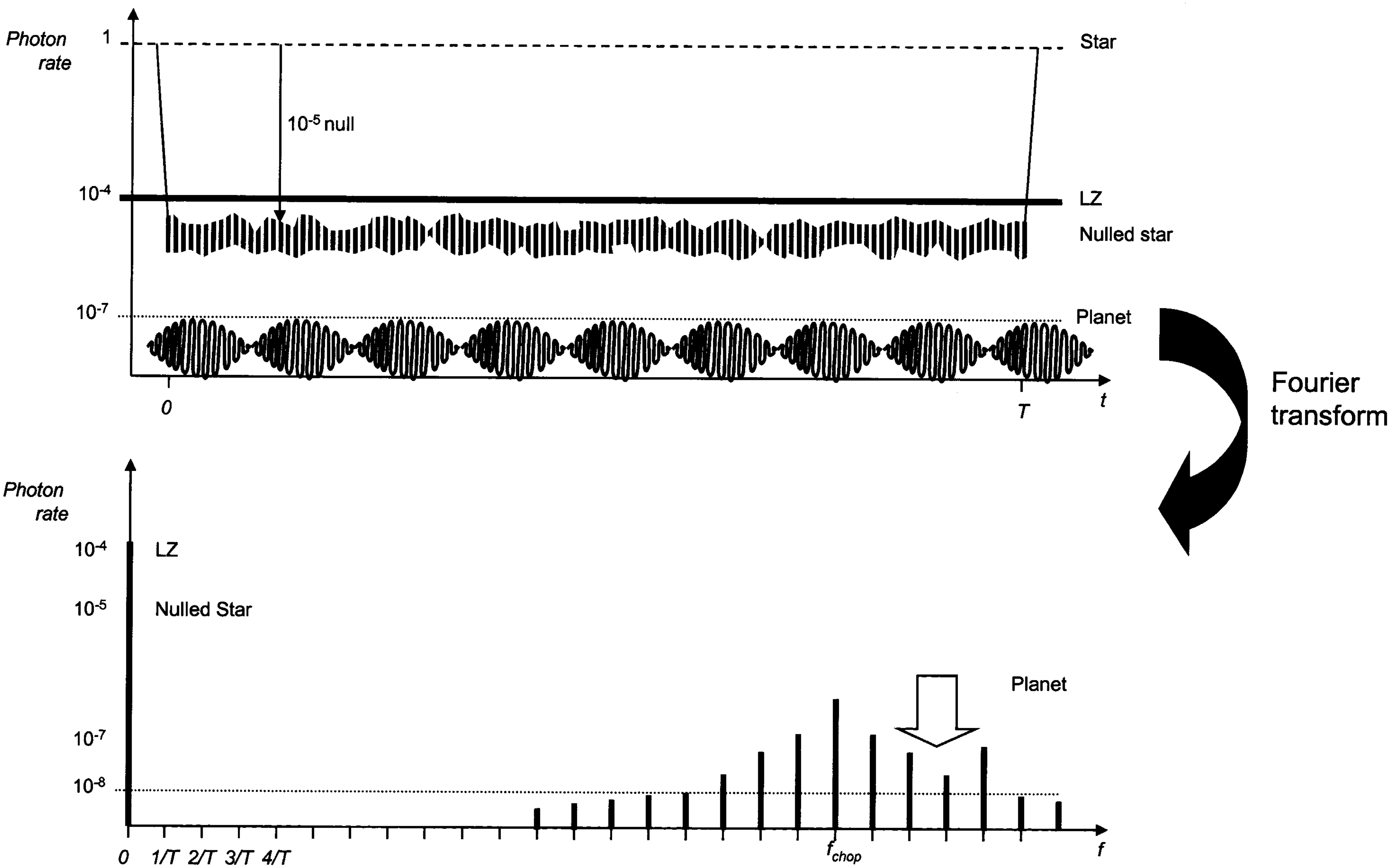
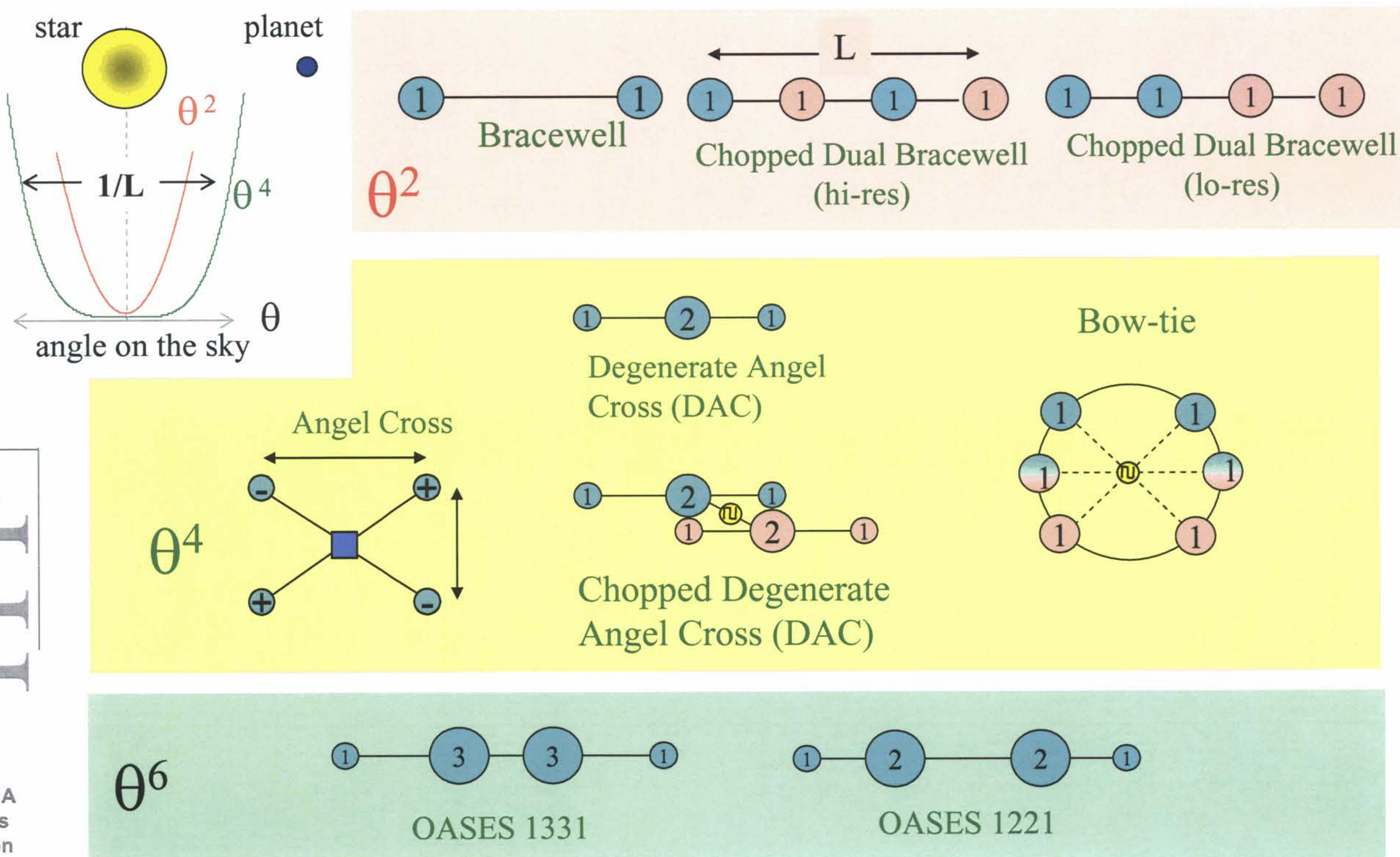
Back to Tighter Tolerances



Better Amplitude & Phase Control Needed

		Old		New	
		No chop	Chop	No chop	Chop
Photon noise (null depth)	δA	0.5%	0.5%	0.5%	0.5%
	$\delta\phi$	7 nm	7 nm	7 nm	7 nm
Systematic noise (null stability)	δA	0.13%	4%	0.09%	0.14%
	$\delta\phi$	2.0 nm	60 nm	1.4 nm	1.5 nm

Architecture Trade: Core Science



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Planet Signal Isolation (chopping)

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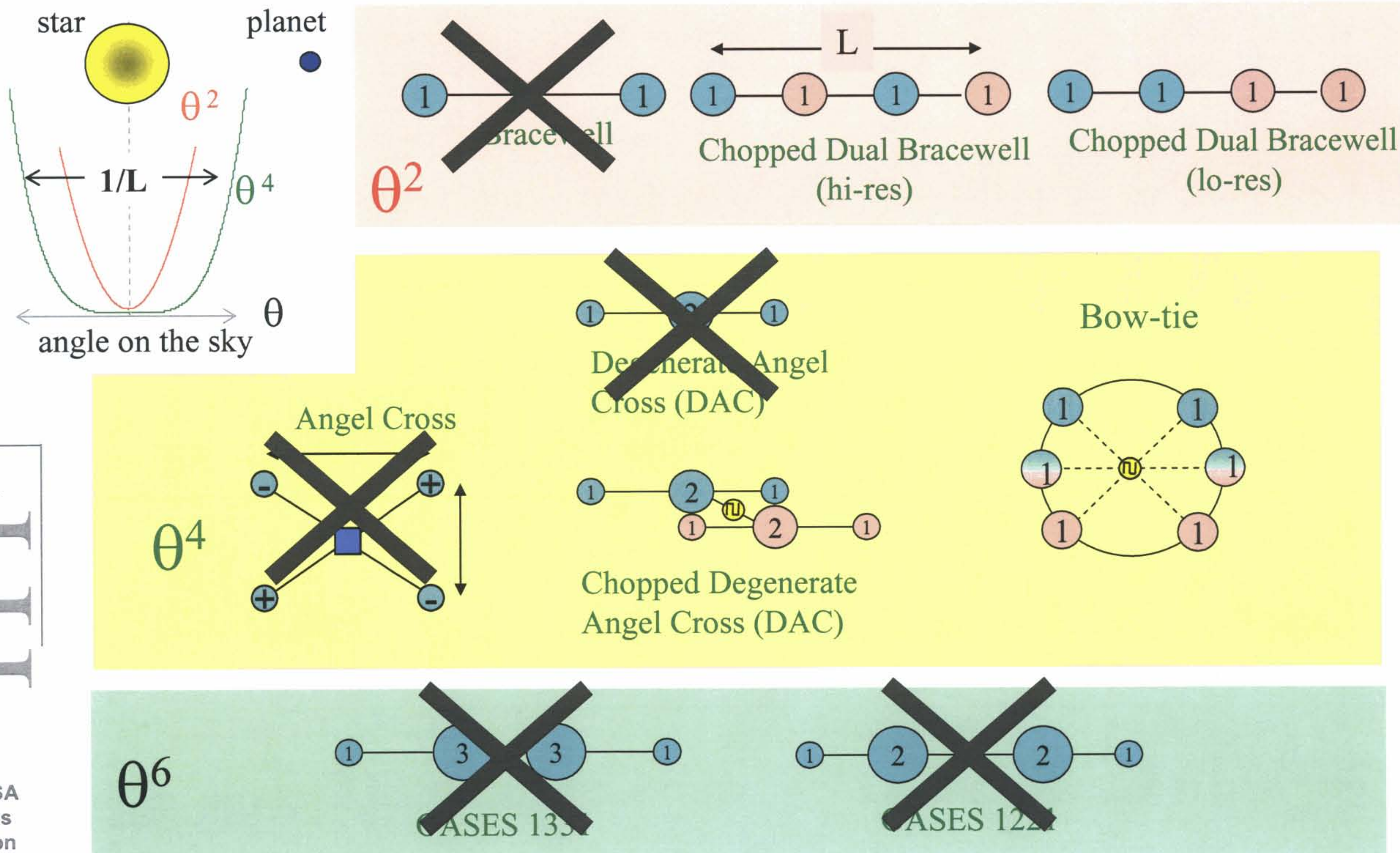

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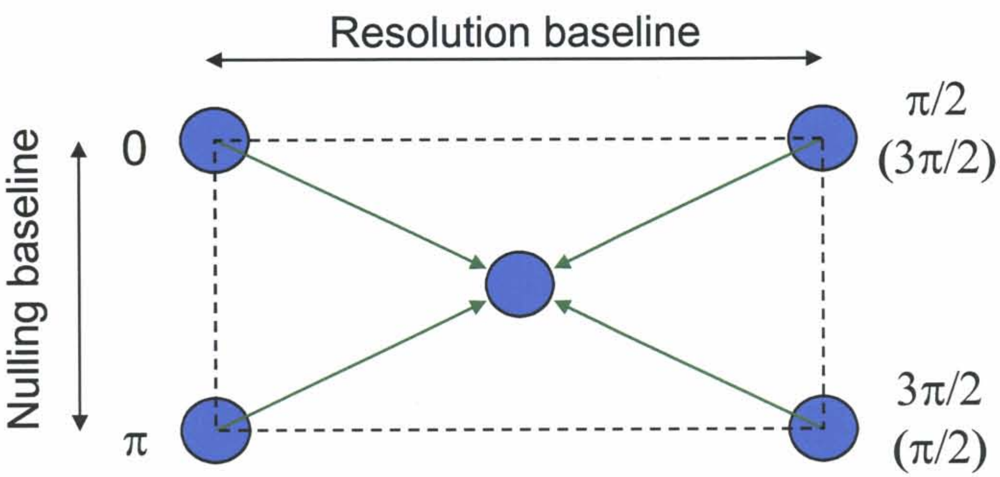
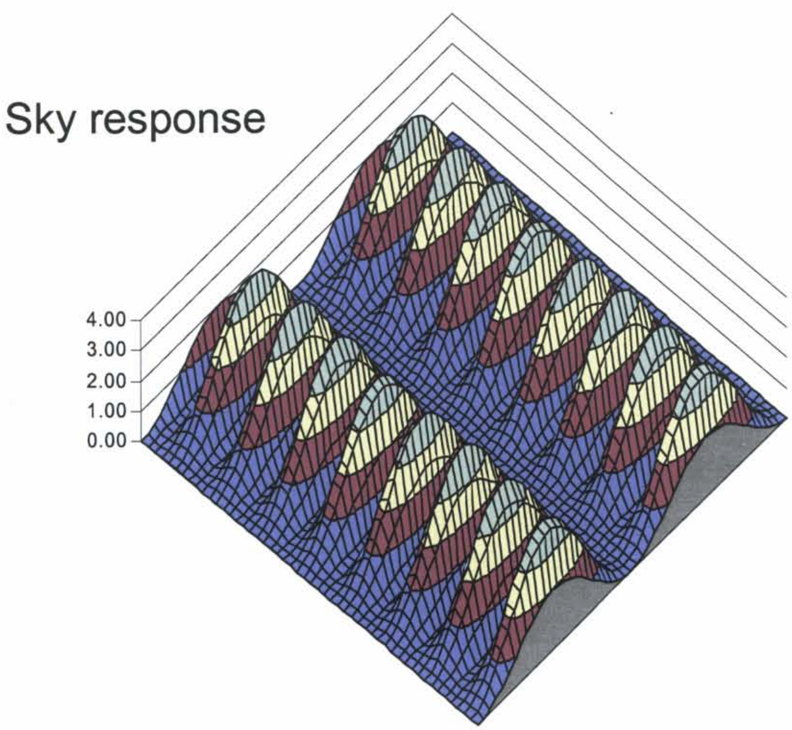
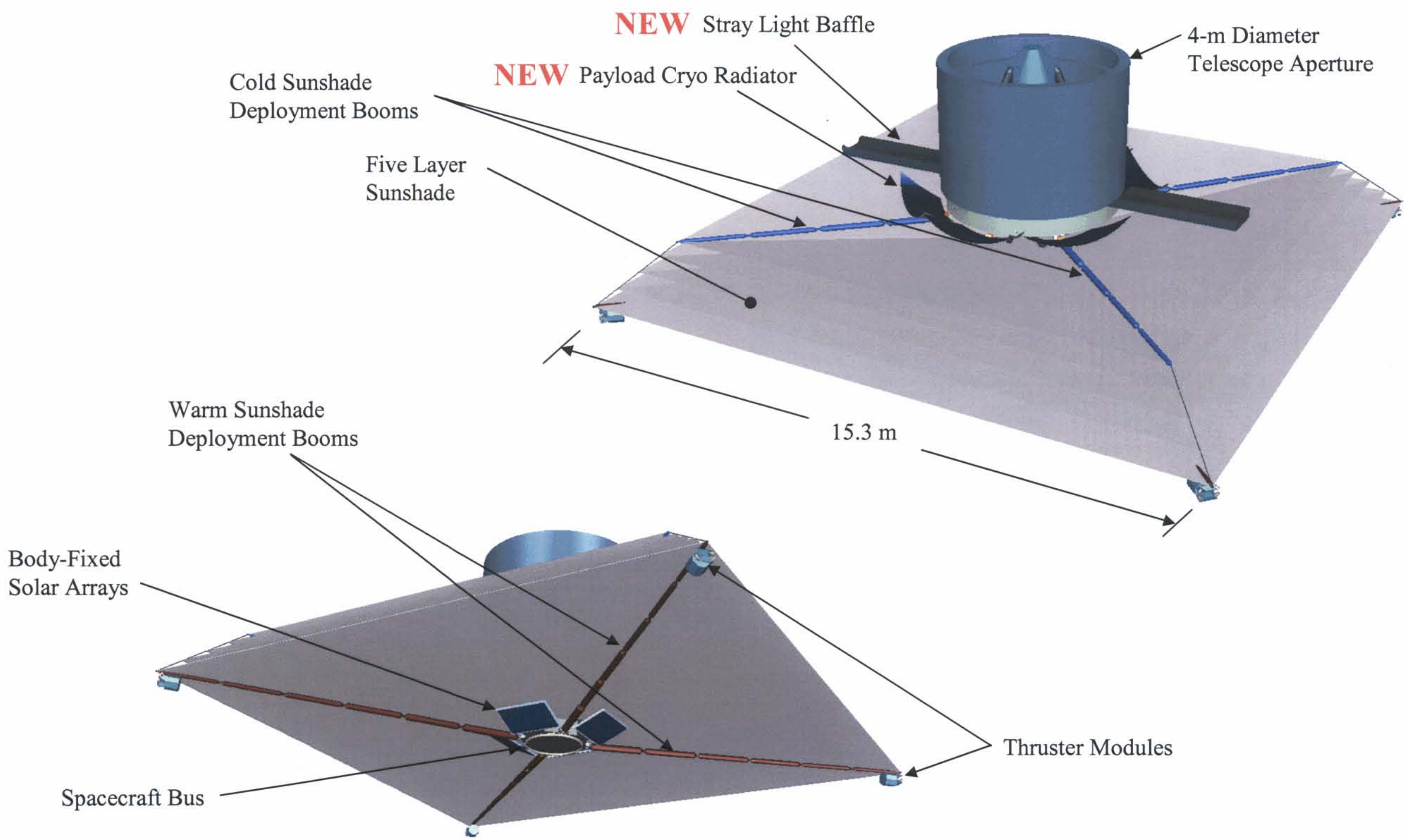
X-Array Configuration



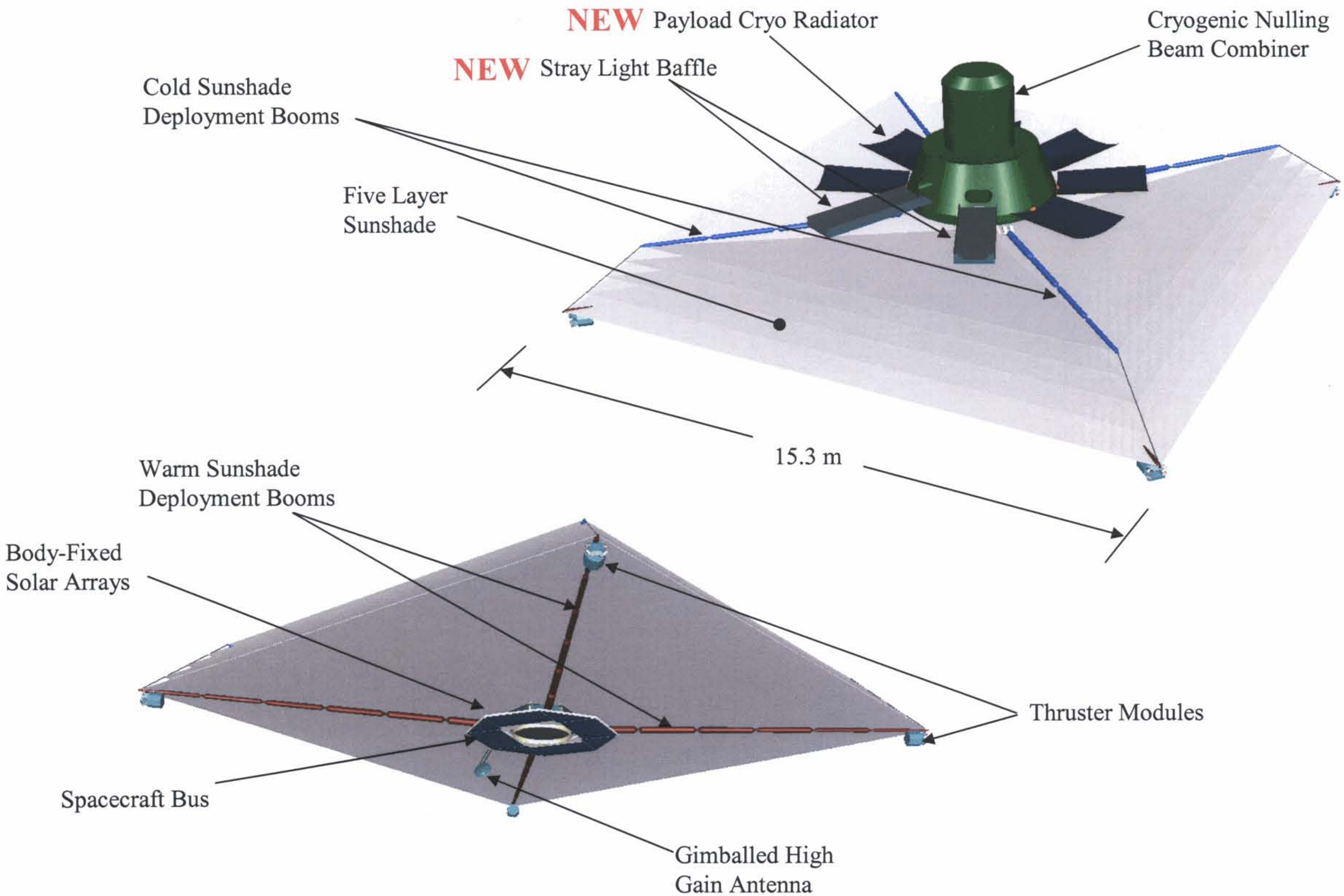


- Advantages
  - Decouples null and resolution baselines
  - Direct collector-to-combiner beam relay
  - Identical, interchangeable collectors
  - Others
- Disadvantages
  - Need articulation of combiner input mirrors

Dan Miller will discuss this . . .



. . . and this


NEW Payload Cryo Radiator
Cryogenic Nulling Beam Combiner
NEW Stray Light Baffle
Cold Sunshade Deployment Booms
Five Layer Sunshade
15.3 m
Warm Sunshade Deployment Booms
Body-Fixed Solar Arrays
Thruster Modules
Spacecraft Bus
Gimballed High Gain Antenna

Expansion of FOR for SCI

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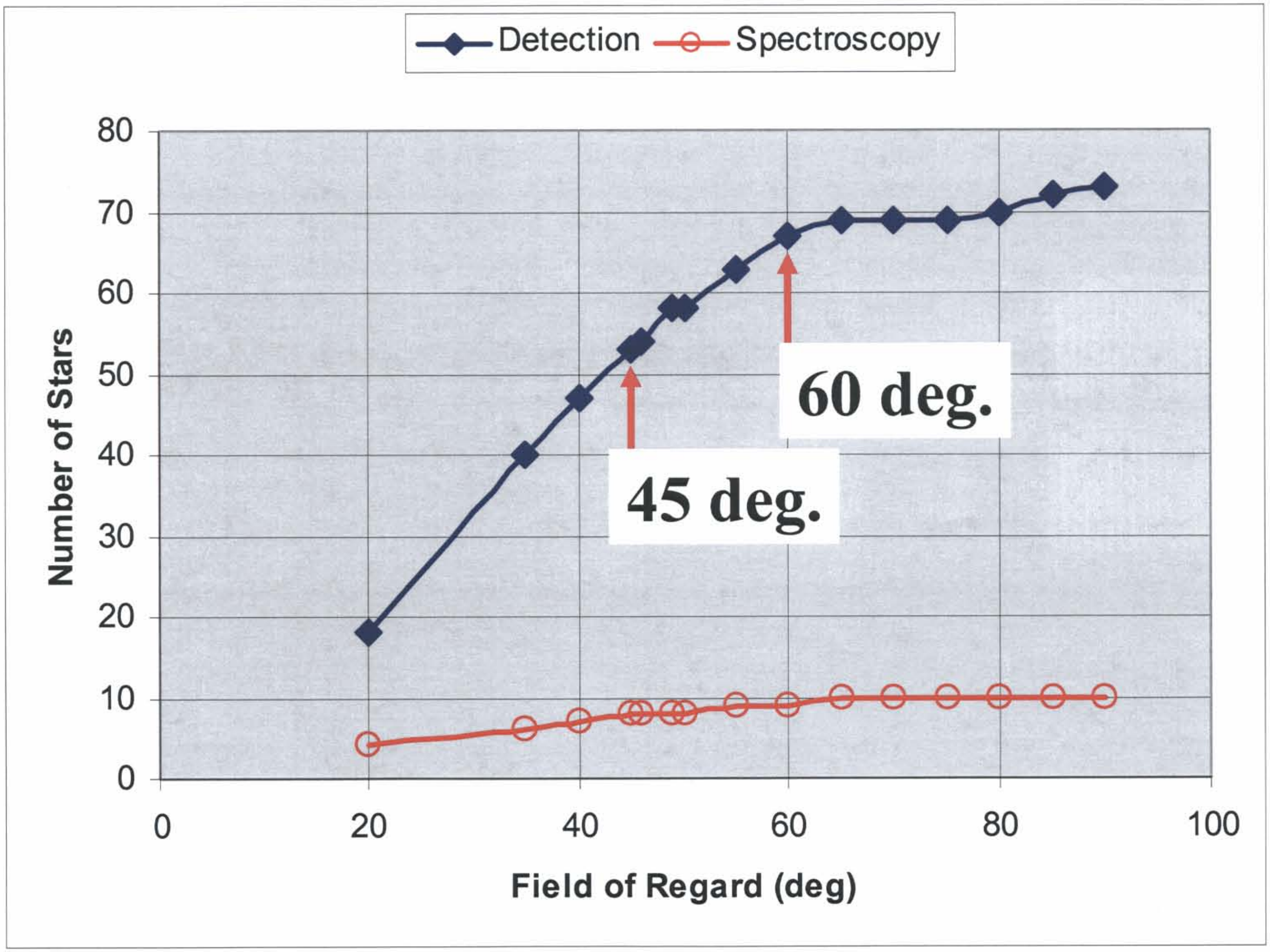

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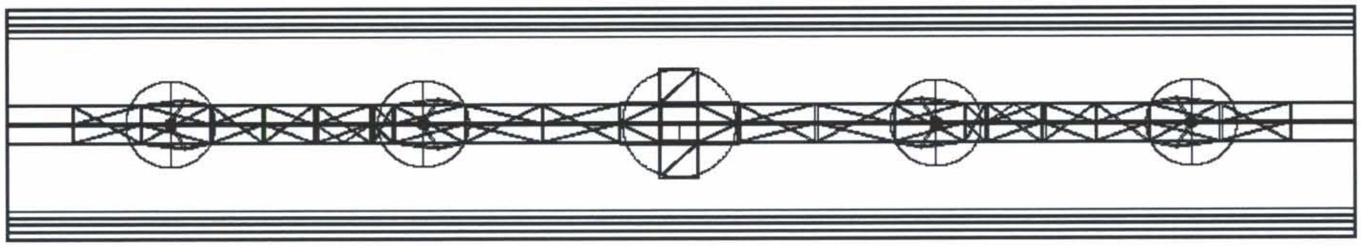
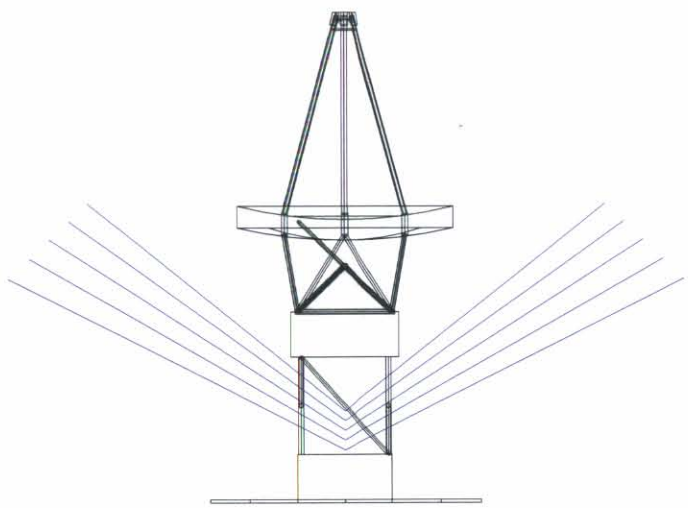
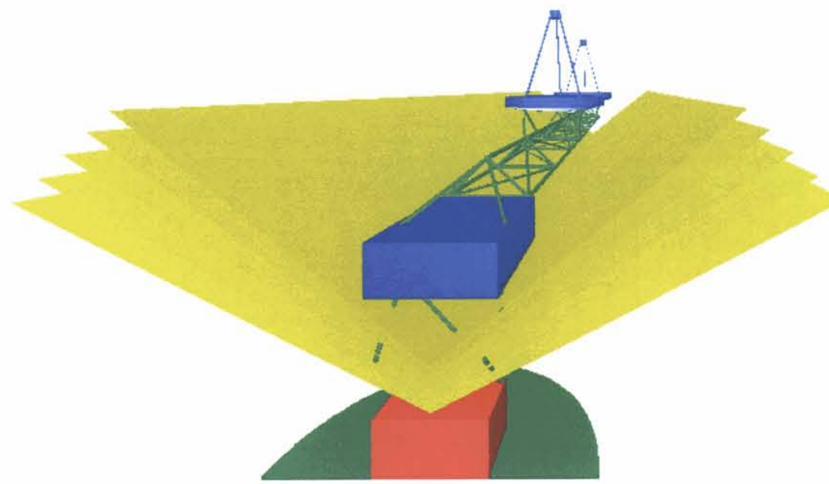
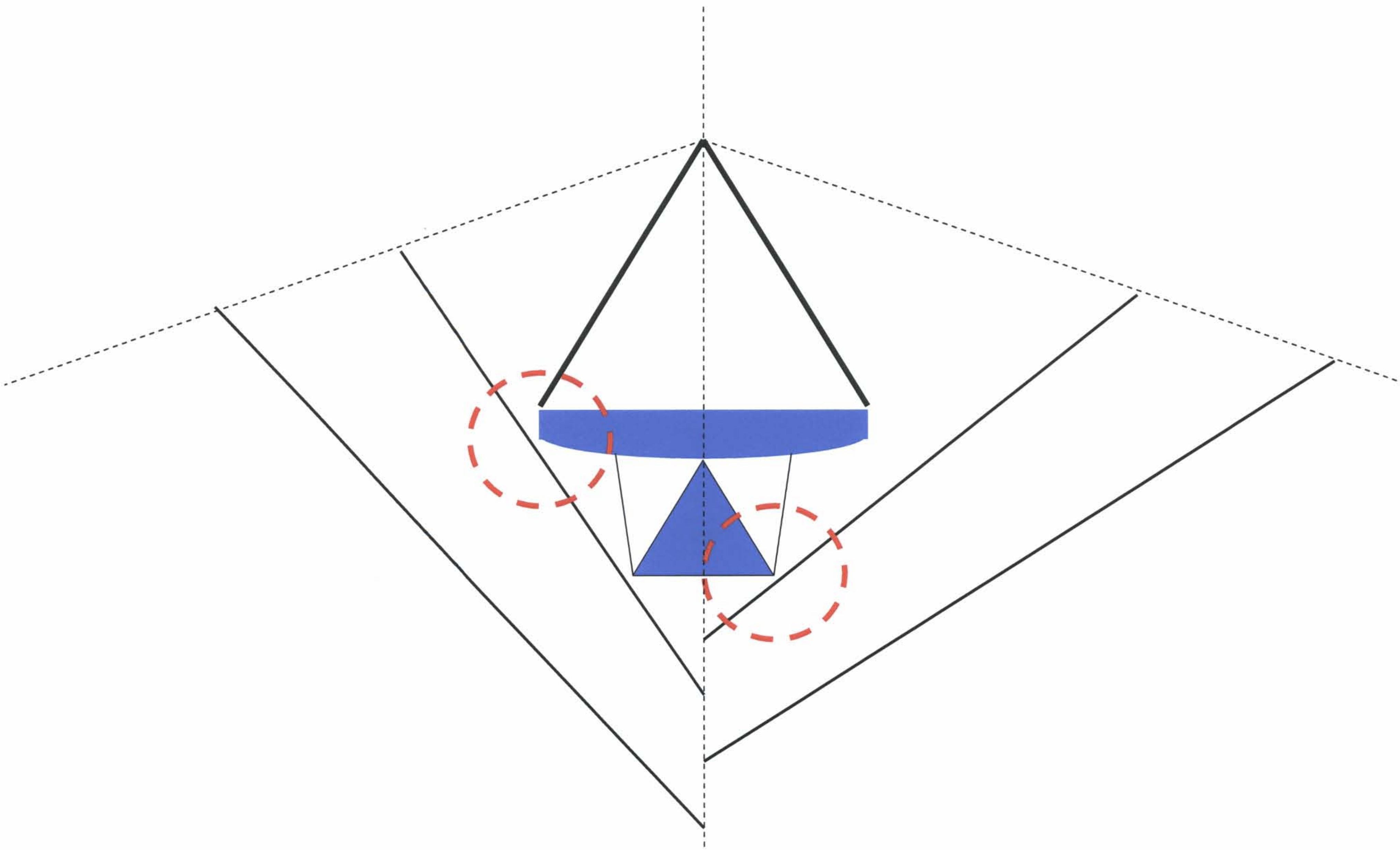
Sunshield Concept







Constraining Width Dimension



Preliminary Conclusions for SCI Sunshade

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- 45° to 60° possible
- Shade wider ~ 2 m
- Shade longer ~5 m
- Mass increase ~ 80 kg
- Severe penalties for angles > 60°
- Closed V-groove design could reduce length

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Concept for SCI Telescope (GSFC)

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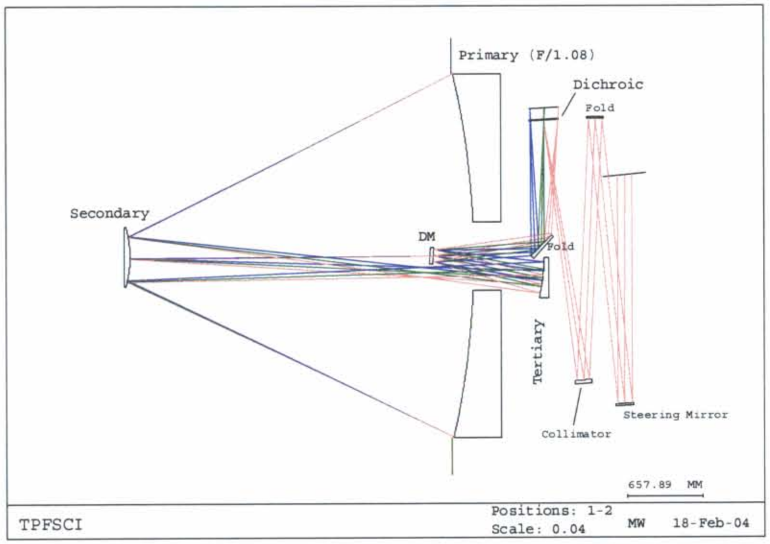
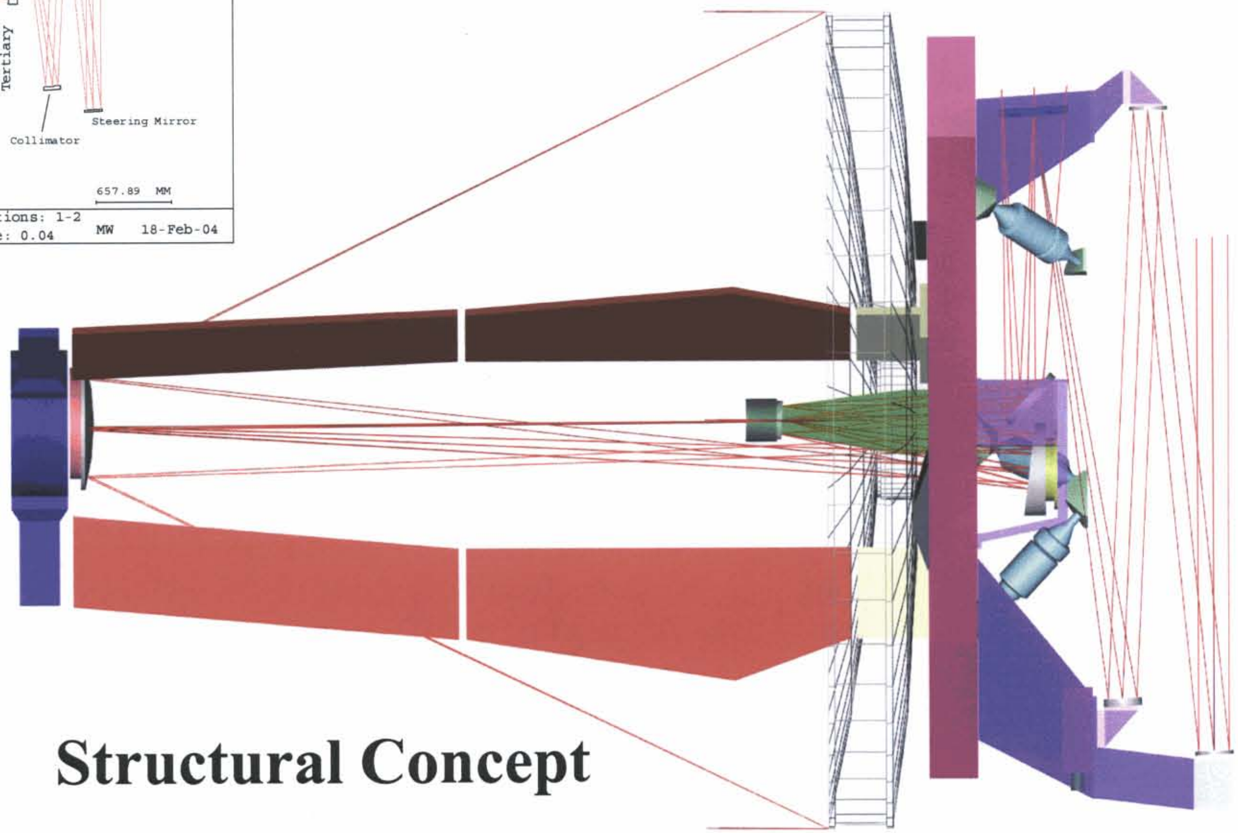


Optical Prescription



Structural Concept

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New TPF-I Technology Efforts

Task Name	PI	Org	Scope
Electromagnetic Formation Flight	D. Miller	MIT	formation control using electromagnetic force
Model Verification	D. Miller	MIT	Quantify modeling uncertainty factors
Propulsion Contamination	M. Martinez-Sanchez	MIT	Plume IR signatures and depositions for Hall thrusters (and possibly others)
Common Path Phase Sensing	P. Hinz	U. of Az	Demonstrate the ability to sense and correct phase errors
Mid-IR Beamsplitter	P. Hinz	U. of Az	3 types: sandwich, windmill, perforated

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Nulling Results

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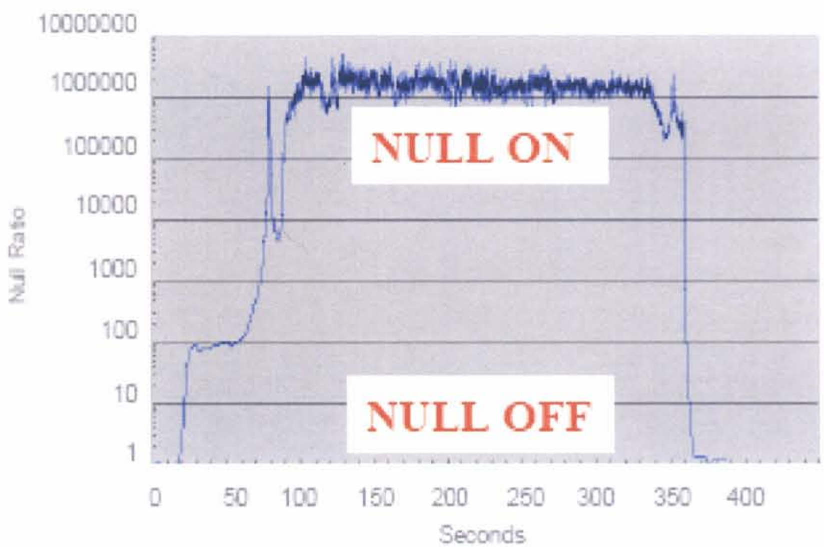
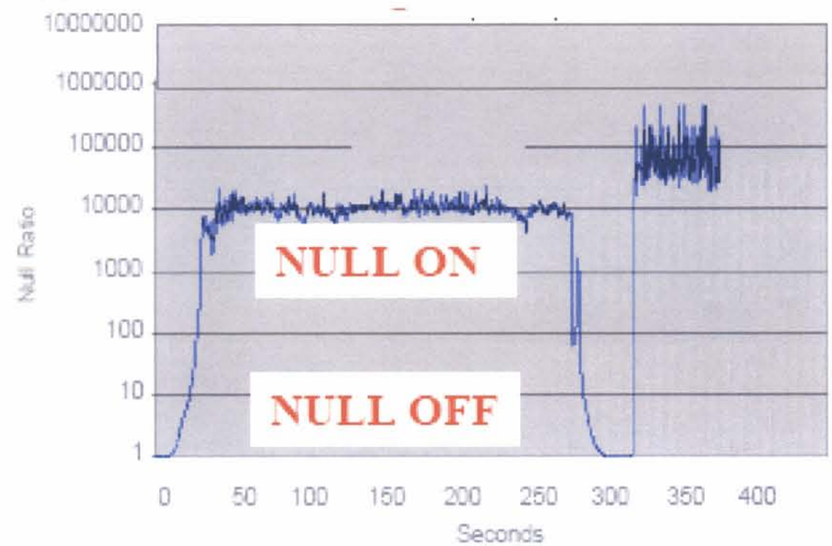
DEEP



BROAD



Future BROAD and DEEP: 10^{-6} @ 25% BW

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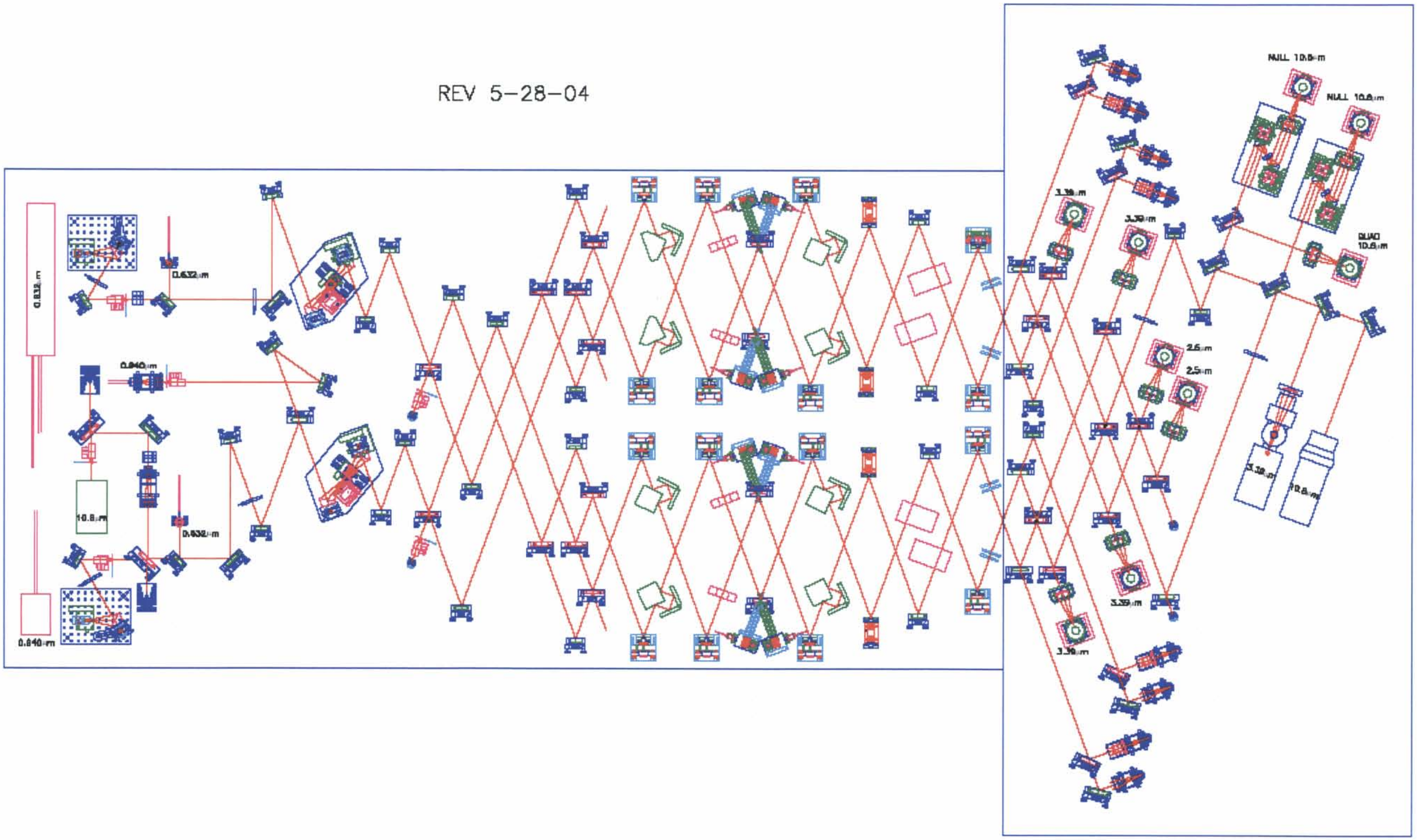
Planet Detection Testbed Layout



Formation Control Testbed

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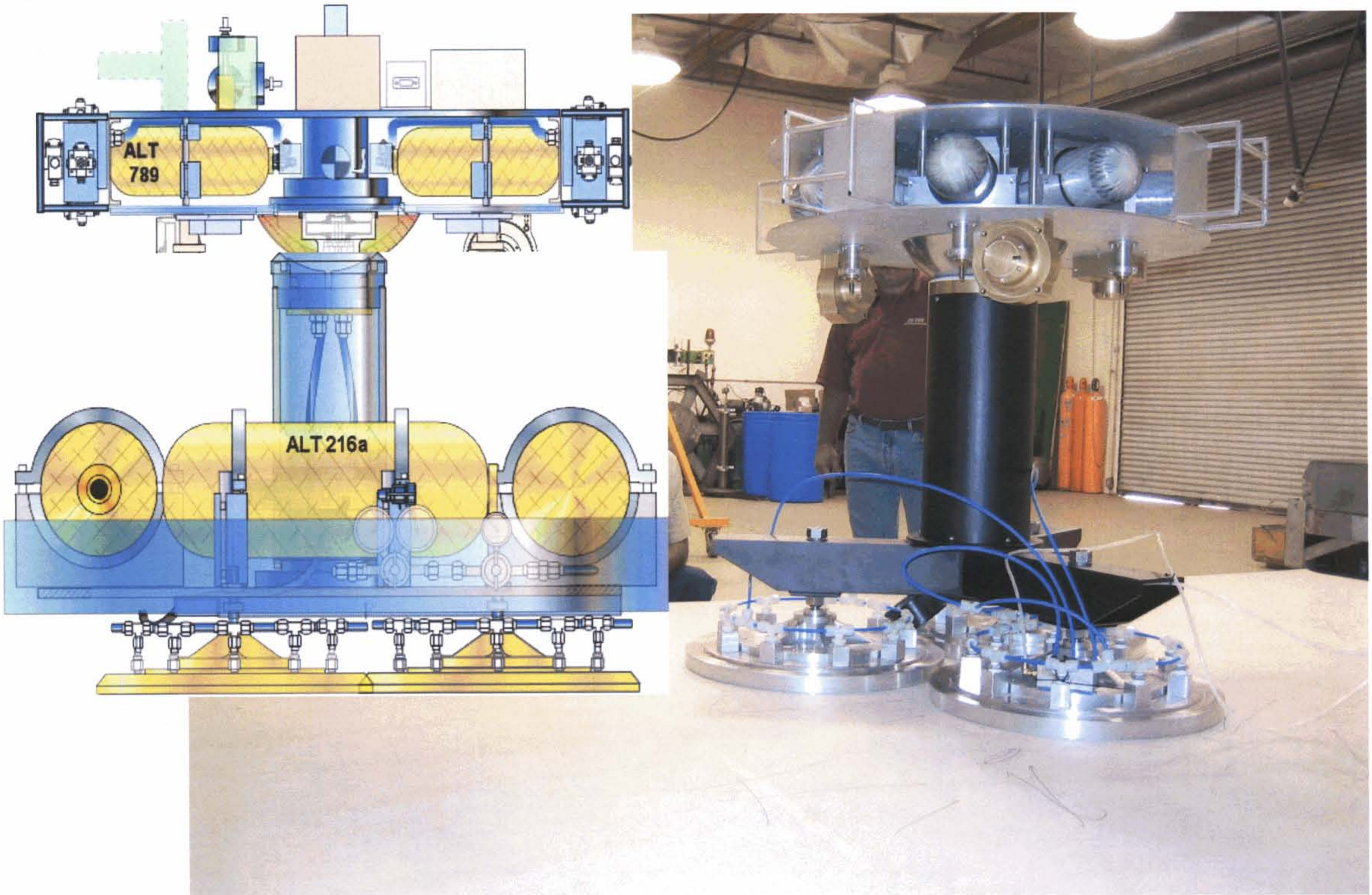

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Some of the additional presentations about the TPF and Darwin interferometers at this conference

Day	Time	Speaker	Paper #	Paper Title
Monday	2:00 p.m.	Mennesson	5491-16	Expected science capabilities of the TPF interferometer
Tuesday	8:30 a.m.	Fridlund (ESA)	5491-26	Darwin and TPF technology and prospects
→ Tuesday	8:30 a.m.	Henry	5491-30	Terrestrial Planet Finder interferometer architecture, mission design, and technology development
Tuesday	8:30 a.m.	Lay	5491-32	Architecture selection and optimization for planet-finding interferometers
Tuesday	8:30 a.m.	Miller	5491-33	Current Status of the TPF formation flying interferometer concept
Tuesday	8:30 a.m.	Noecker	5491-40	TPF control system requirements for structurally connected and formation flying interferometers
Tuesday	1:30 p.m.	Pedreiro	5491-41	Control and vibration mitigation for structrually connected Terrestrial Planet Finder Interferometer
Tuesday	5:30 p.m.	poster	5495-43	Structural Configuration for the Terrestrial Planet Finder Structurally Connected Interferometer Concept
Tuesday	7:30 p.m.	poster	5487-183	The potential of conductive waveguides for nulling interferometry
Thursday	11:10 a.m.	Coulter	5487-55	NASA's Terrestrial Planet Finder Mission
Thursday	11:10 a.m.	? (ESA)	5487-56	A comparison of architectures for Darwin/TPF
Thursday	11:10 a.m.	Unwin	5487-57	Terrestrial Planet Finder: science overview
Thursday	11:10 a.m.	Lindensmith	5487-58	Terrestrial Planet Finder technology development
Thursday	5:30 p.m.	poster	5491-188	Deformable mirror based adaptive nuller demonstration in the near-IR
Thursday	5:30 p.m.	poster	5491-189	Stellar suppression with interferometer arrays
Thursday	5:30 p.m.	poster	5491-190	A cryogenic mid-IR nuller for TPF
Thursday	5:30 p.m.	poster	5491-211	Terrestrial Planet Finder cryogenic delay line
Friday	9:45 a.m.	Wallace	5491-96	Mid-IR interferometric nulling for TPF
Friday	9:45 a.m.	Lay	5491-97	The impact of systematic errors on nulling interferometers
Friday	9:45 a.m.	Levine	5497-18	Integrated modeling approach for the Terrestrial Planet Finder Mission
Friday	9:45 a.m.	Henry	5497-19	Modeling the TPF Interferometer

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Backup

TPF Science

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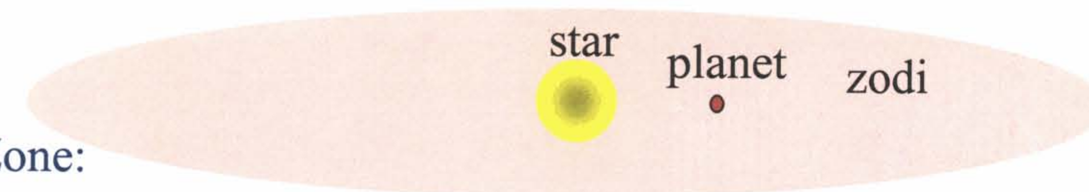
- **Detection**: Complete survey within 2 yrs (Late F,G,K dwarf stars)

	Core Science	Full Science
Full Survey	>**30** stars	>**150** stars
Partial Survey	>**120** stars	as capability allows

- **Full Survey Parameters**:
  - Completeness 95%
  - Continuously Habitable Zone:
    - 0.7 to 1.5 AU (G-dwarf) – Earth area
    - 0.9 to 1.1 AU (G-type) – Half Earth area
  - At least 3 visits
  - Earth albedo



- **Wavelength:**
  - 6.5 - 13μm (17-20 desirable), SR=25
  - 0.5 - 0.8μm (1.05 desirable), SR= 75
- **Field of View** (0.5 to 1 arcsec) to characterize Jovian planets in subset of stars
- **Spectral resolution** of R>100 for brightest sources

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Science Requirement Changes

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- # of star systems to be surveyed
  - Was >/=150
  - Is >/=165
- New star list
  - Was
  - Is ~TBD candidate stars
    - 2350 full set within 30 parsecs
    - ~1000 after science culls

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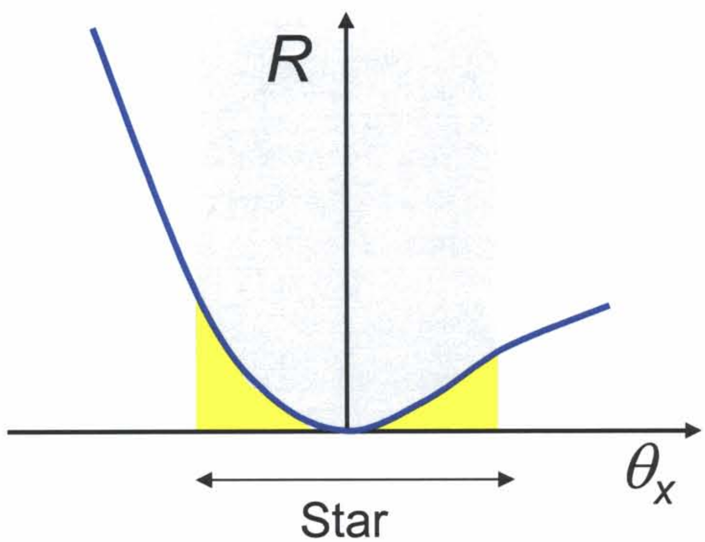
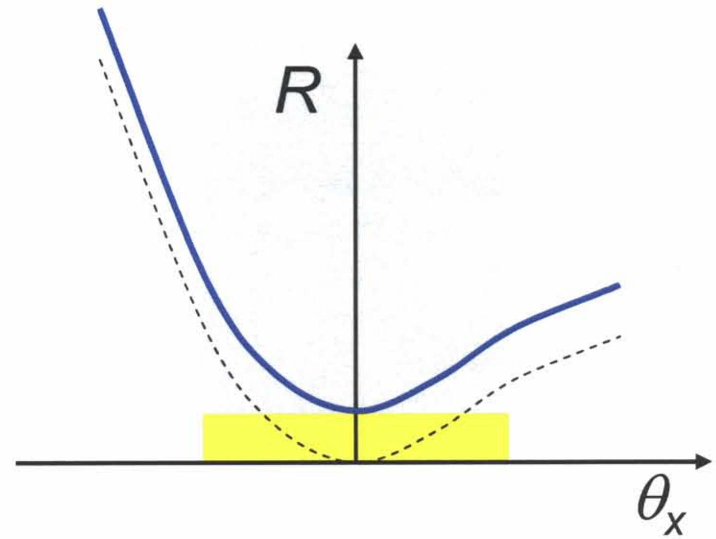
Noise sources

Stellar geometric leakage



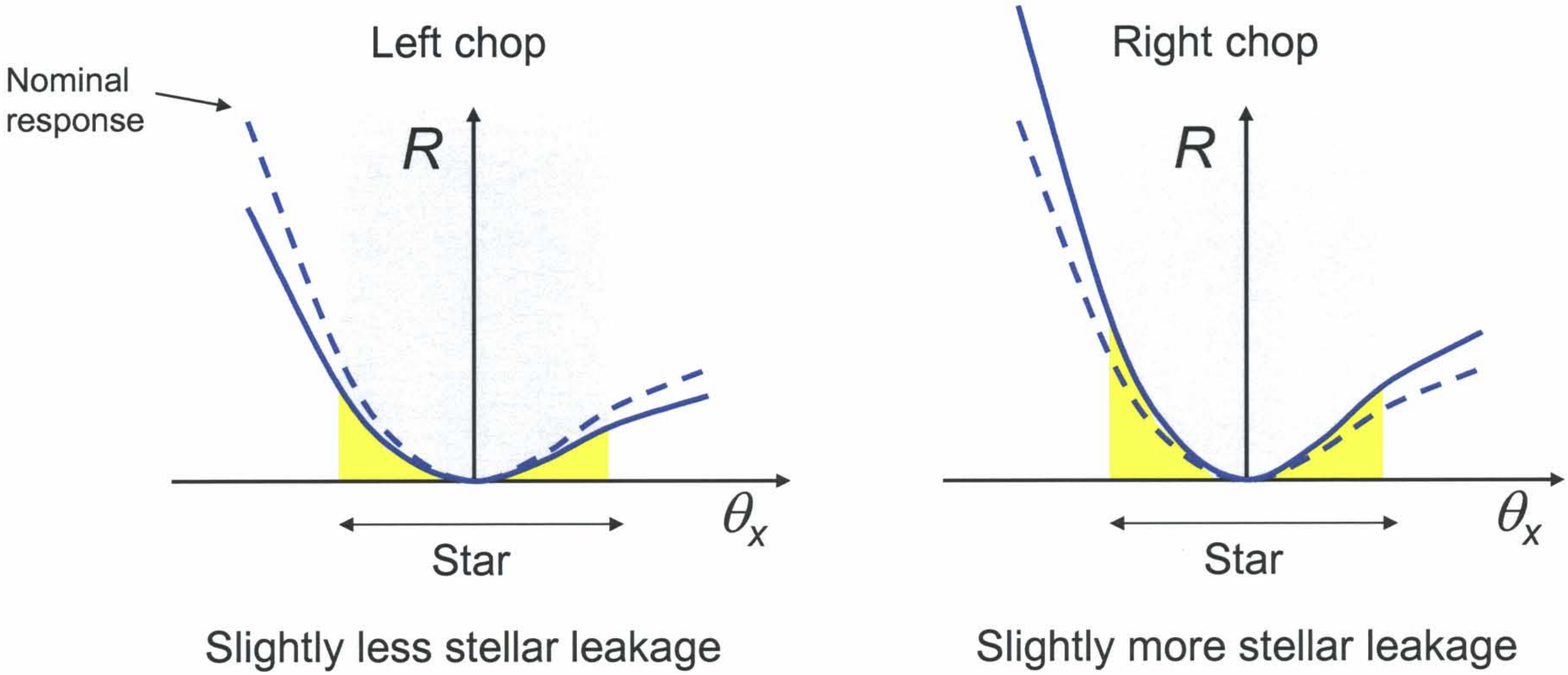
Null floor leakage



- Also EZ and LZ geometric leakage
- Occurs for ideal instrument
- Reduced with θ^4 (broader) null

- Result of amplitude, phase & polarization errors
- Not Reduced with θ^4 null

Co-phasing error



- Left and Right chops do not cancel
- Does not impact on-axis null
- Requires extended source

Nulling Architecture Options

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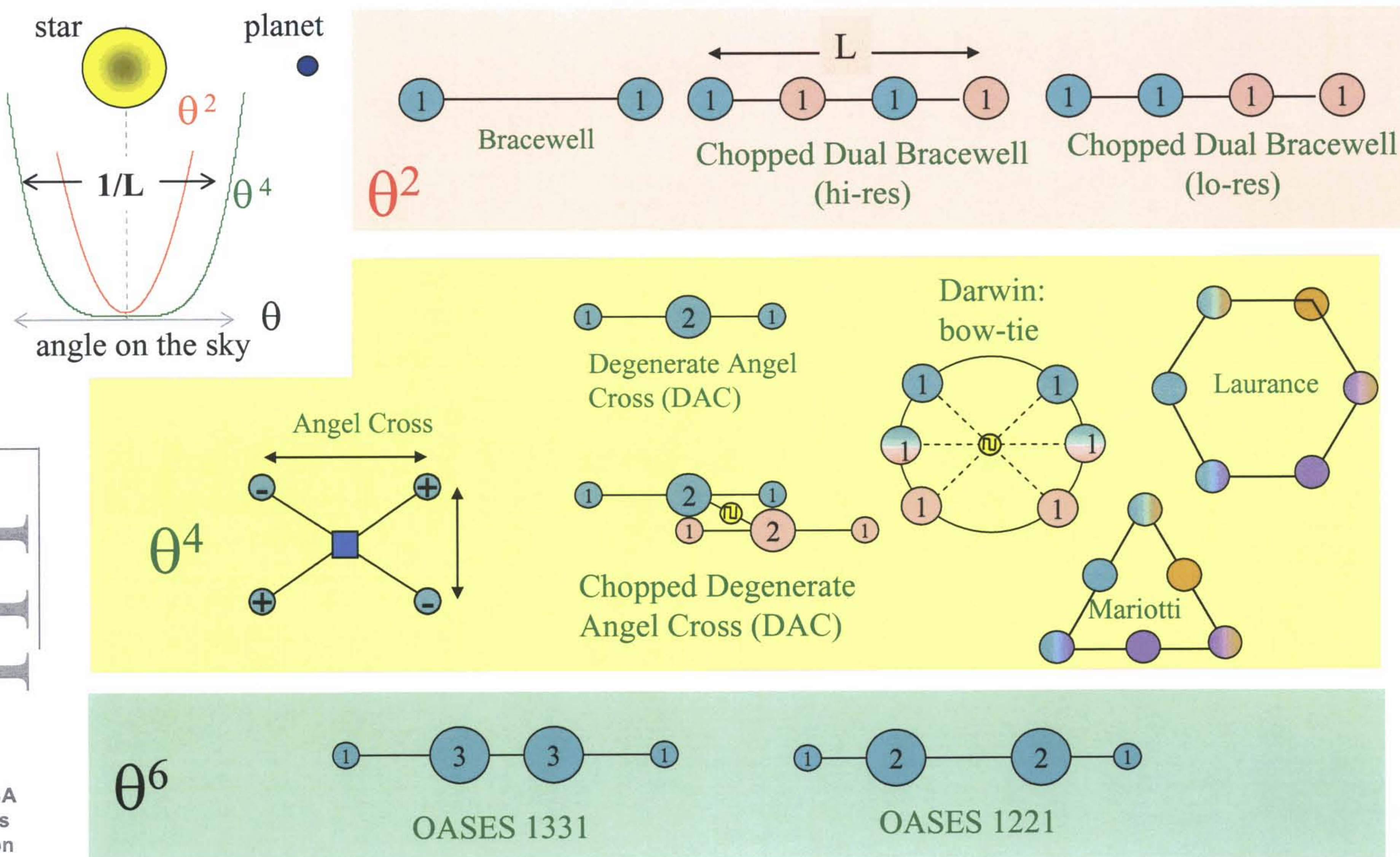

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Star Selectors Analysis for Dual Chopped Bracewell

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	Value	Selected Stars	Remaining Stars
TPF Project Star Selectors			
Stars within	30 parsecs		
Abundance Filter	Ebbets list		258
Type	FGK	250	250
Binarity (planet formation)	TBD		
TPF Interferometer Star Selectors			
No Binary Companion (planet det.)	<10 asec	228	220
Field Of Regard	+/- 45°	181	151
Resolution	36 m uneven DCB	116	63
Integration Time Detection	3.2 m apertures, 50% of 2 years		54
Spectroscopy (η_{earth}=0.1)	50% of 3 years		5

Strawman for Structurally-Connected Interferometer

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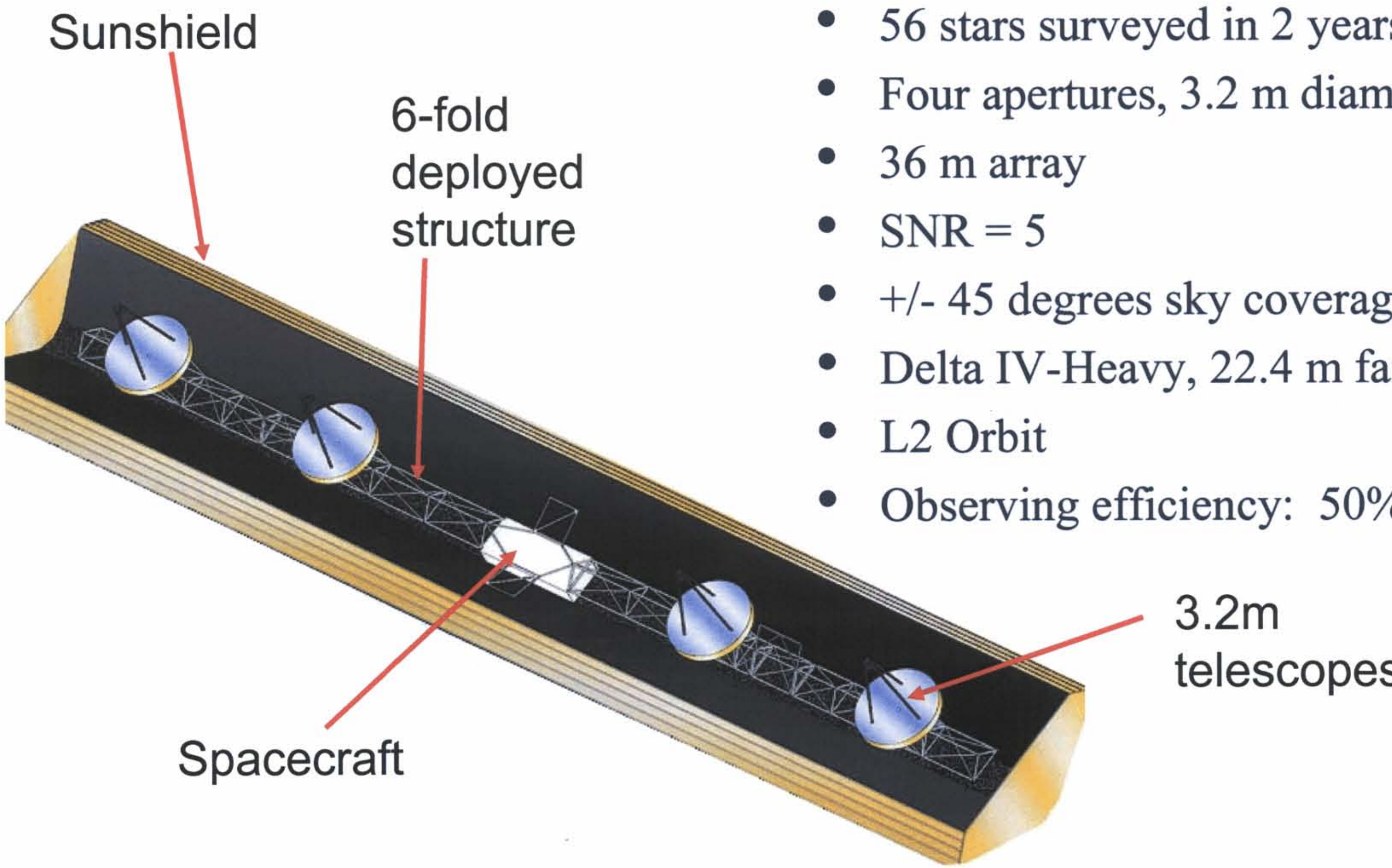

- Dual-chopped Bracewell
- 56 stars surveyed in 2 years
- Four apertures, 3.2 m diameter
- 36 m array
- SNR = 5
- +/- 45 degrees sky coverage
- Delta IV-Heavy, 22.4 m fairing
- L2 Orbit
- Observing efficiency: 50%

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Launch Configuration

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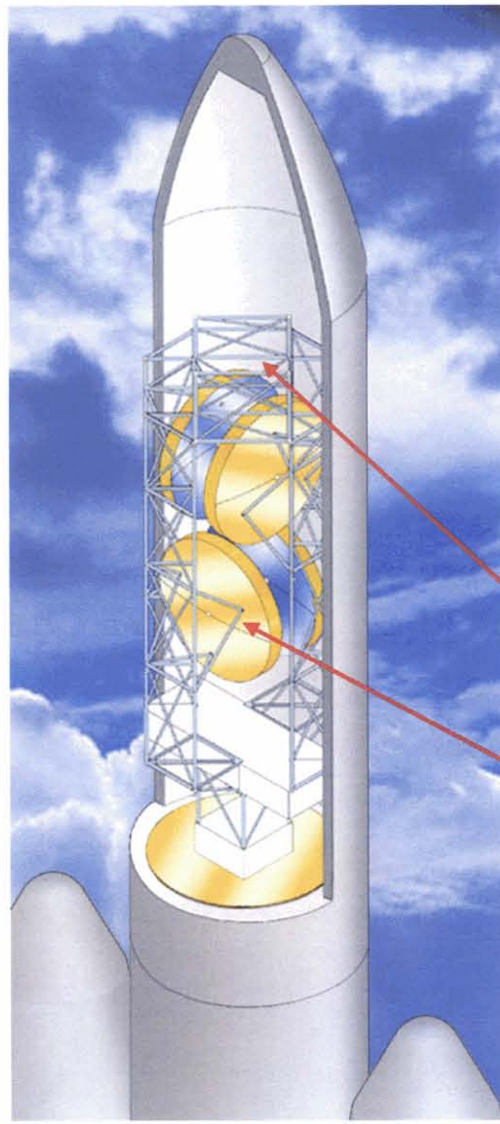

6-fold oblique structure

3.2 m telescopes

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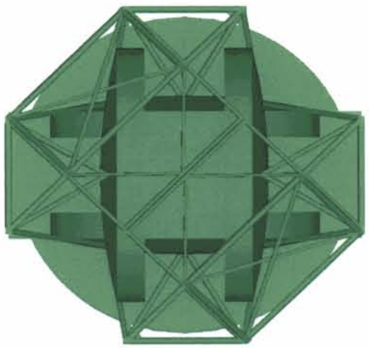
Optional Launch Stiffness Upgrades



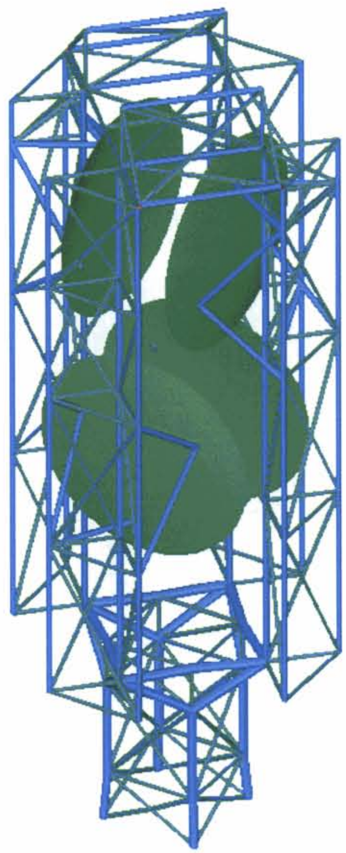
STEP Top View

Objective is to increase minimum structural natural frequencies

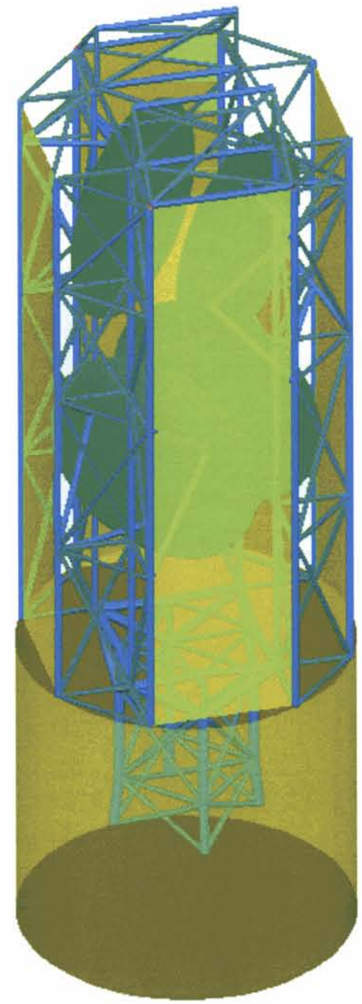
Currently examining panel and cylinder rigidizing structure which would be discarded prior to L2 transfer maneuver

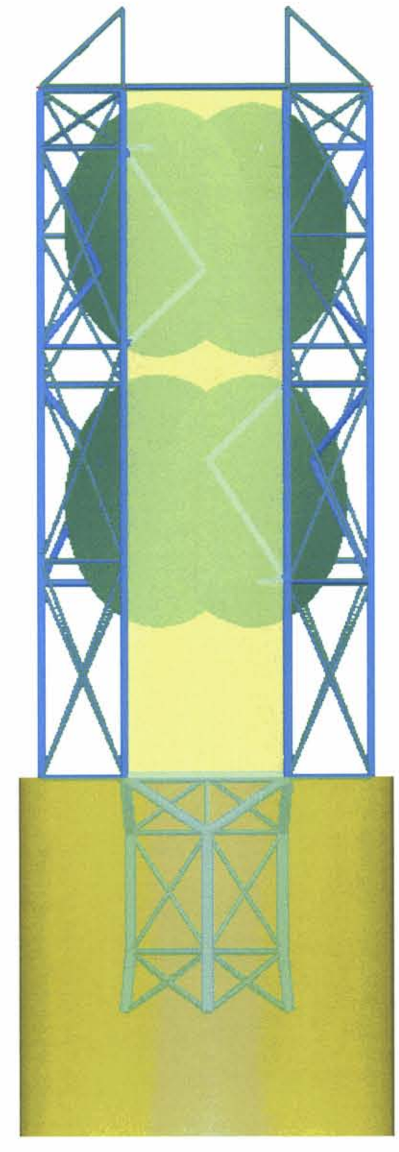
Would substantially increase primary bending and torsional stiffness with minimal mass and volume impact

Does not interfere with spacecraft or primary collector locations



Original FEM





Panel & Cylinder Launch Stiffeners

6-Fold Oblique

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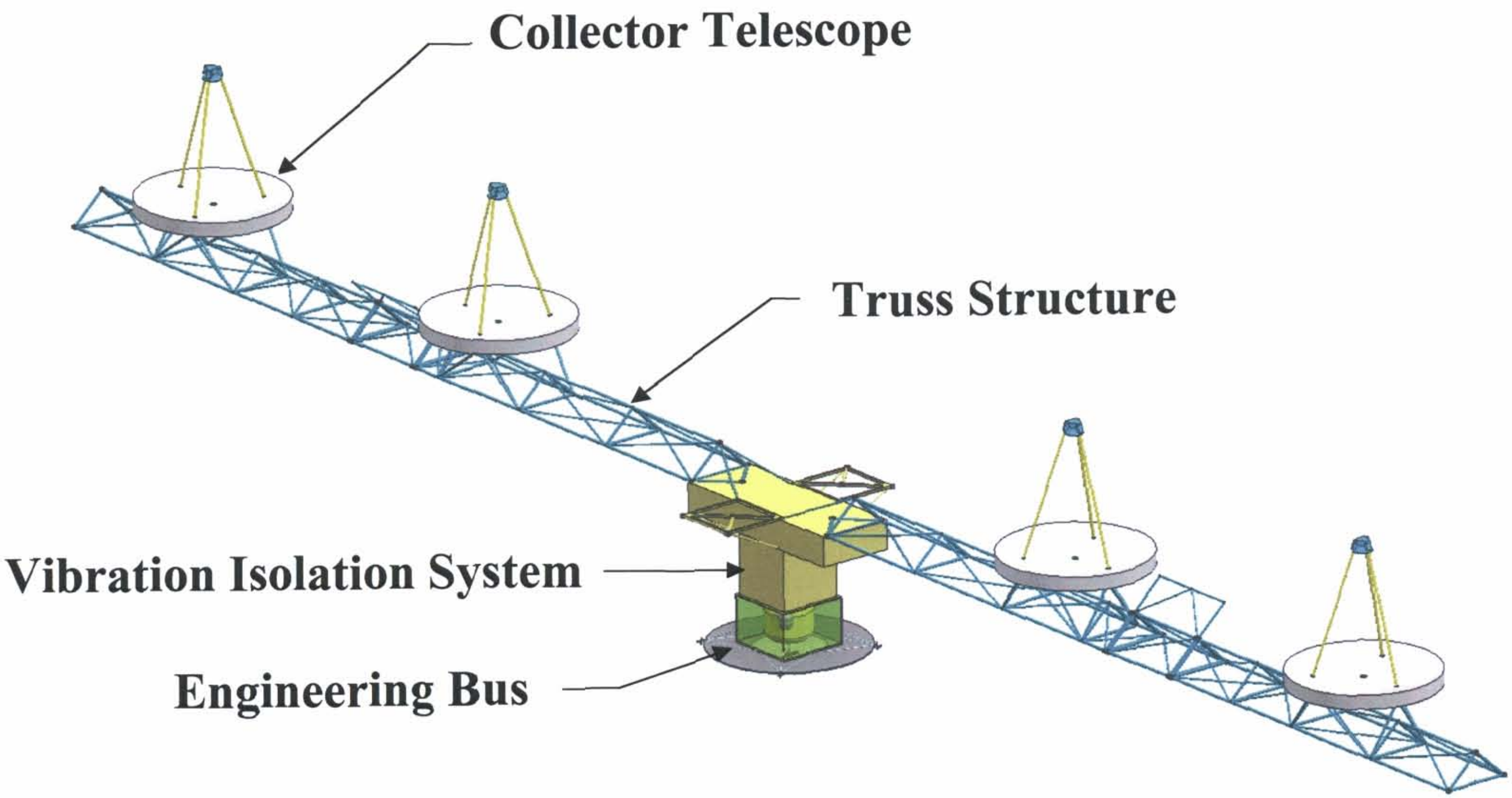

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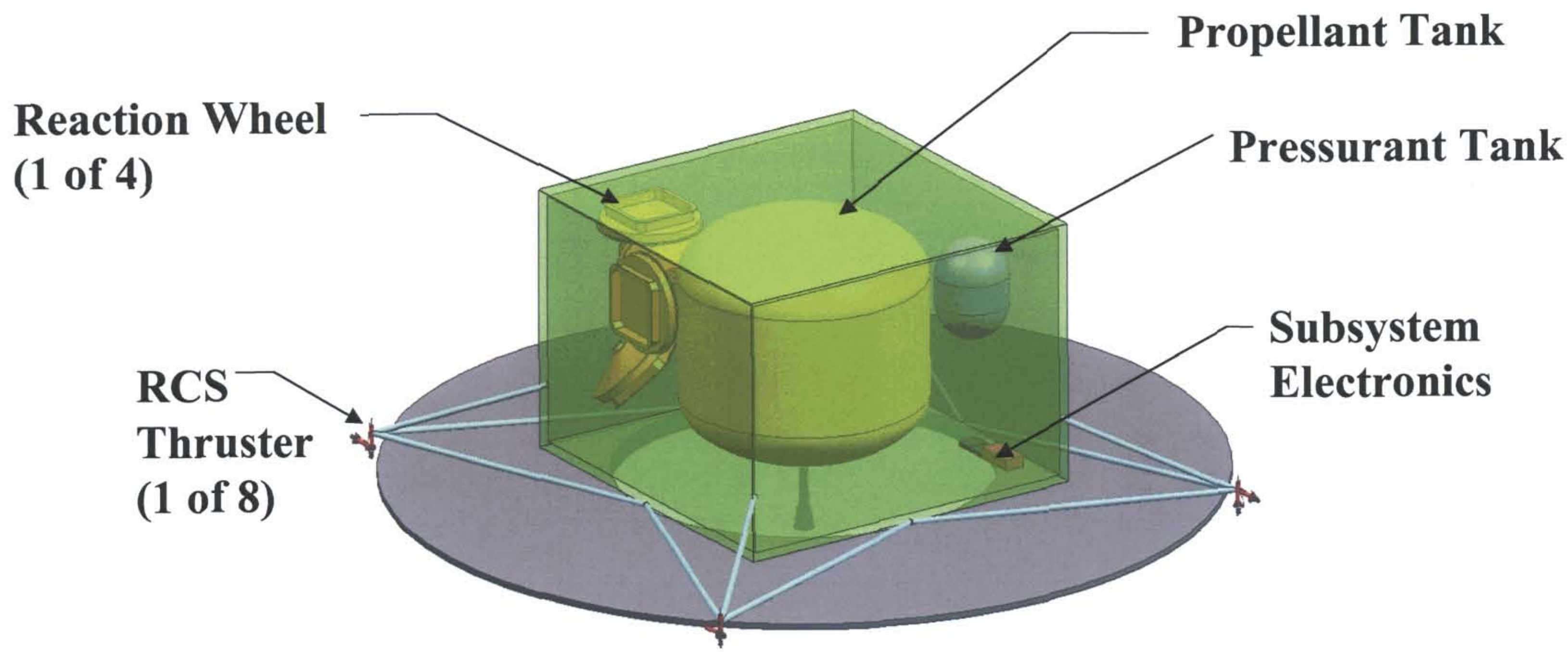
SCI Engineering Bus



SCI Engineering Bus

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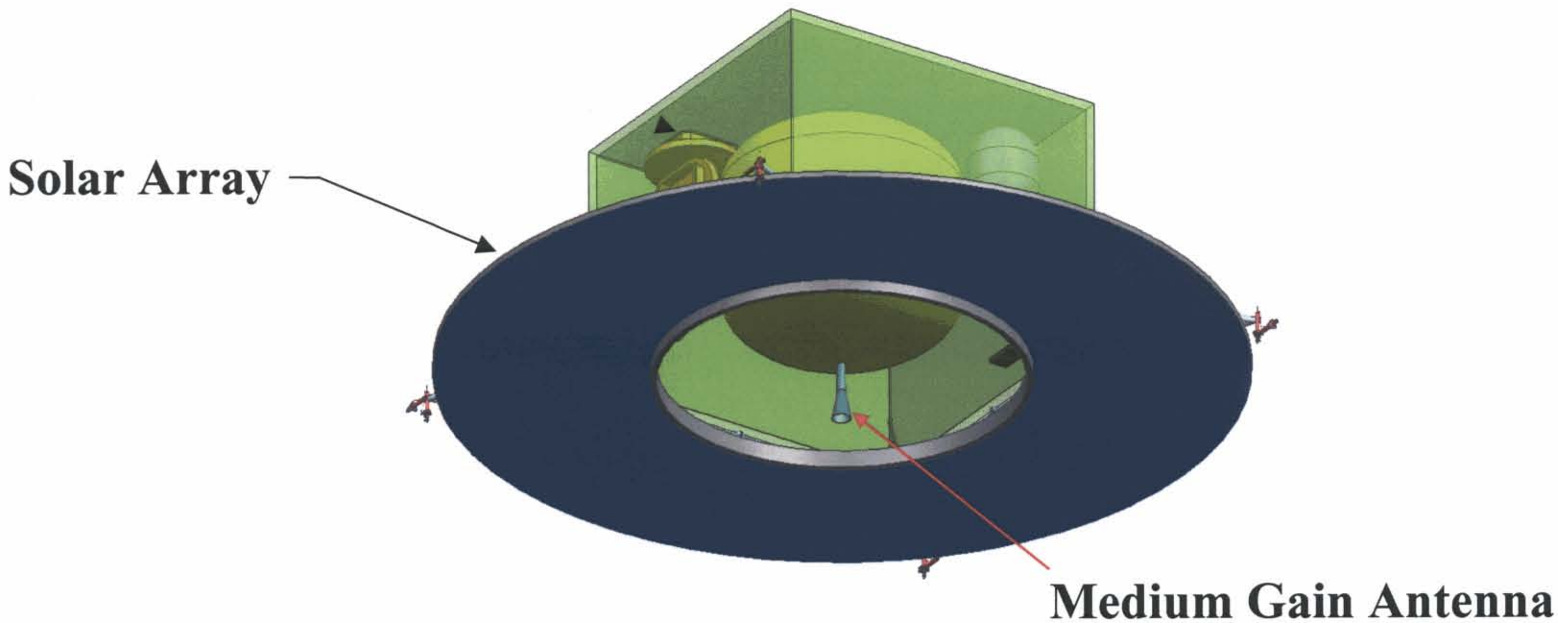

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Structure Configuration - Deployed

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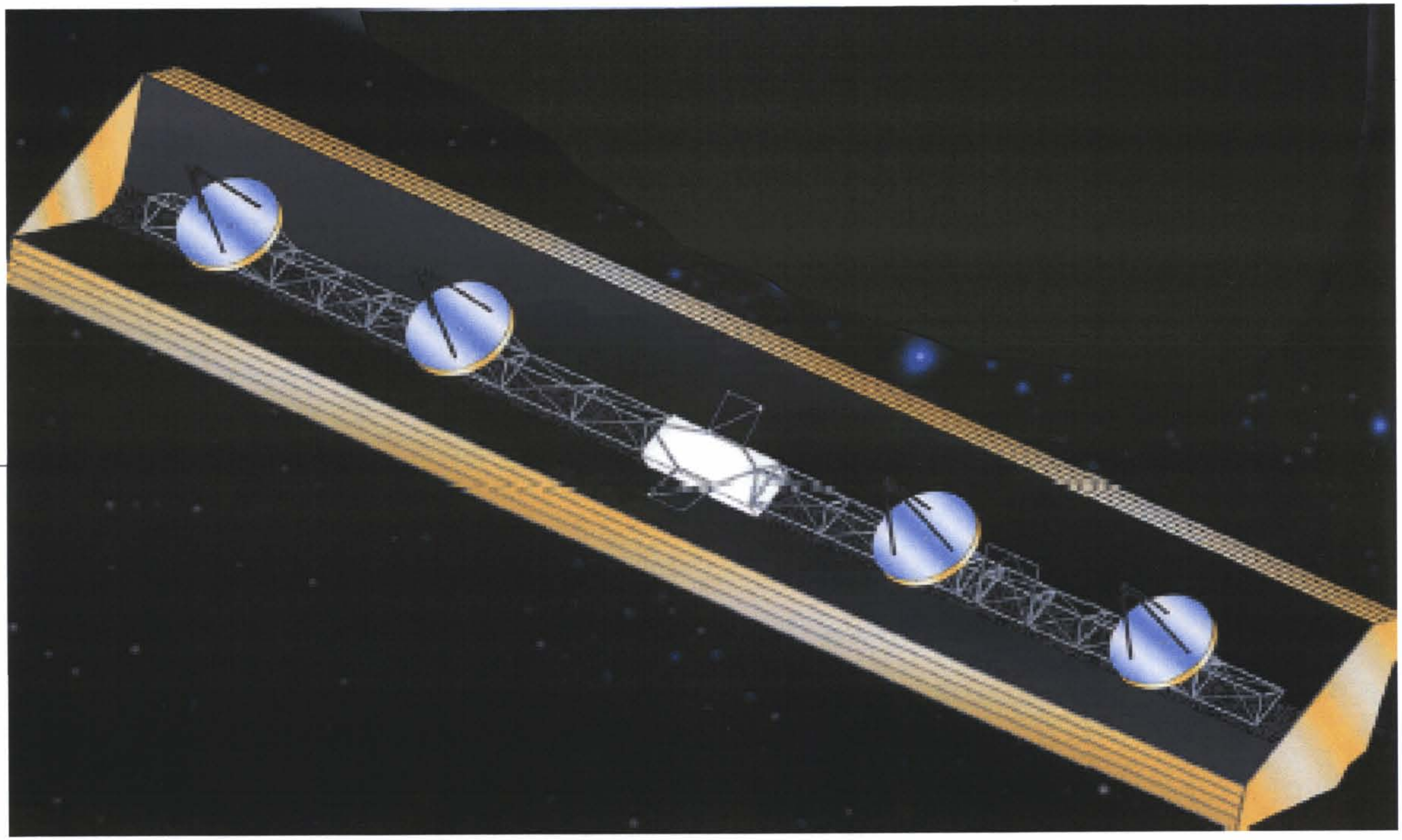

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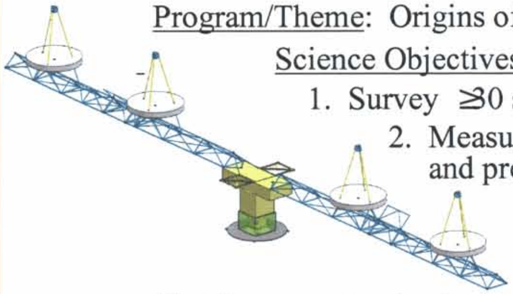
SCI Design Summary

A Search for Earth-Like Planets In the Habitable Zone Around Nearby Stars



Program/Theme: Origins of Stars, Planets, and Life

Science Objectives:

1. Survey ≥30 stars for terrestrial planets
2. Measure planets' orbit, mass, and presence of biomarkers in the atmosphere (H_2O, O_3, CO_2, CH_4)
3. Observe astrophysical sources (active galaxies, etc.)

Mission Description: 1. Structurally Connected Interferometer--consisting of 4 telescopes supported on a linear truss

2. Infrared Nulling Interferometer operating at cryogenic temps
3. Observatory flies in L2 Halo orbit for low disturbance enviro.

Key Enabling Technologies	TRL	Type
Precision Pathlength Control	5	Enabling
Precision Wavefront Control	4	Enabling
Adaptive nuller	2	Enabling
Cyro-actuators	5-6	Enabling
Large Deployable Sunshield	5-6	Enabling
Nulling Beam Combination	3	Enabling
Metrology	3	Enabling
Detectors	5-6	Enabling
Thrusters	4-6	Enabling
Primary Mirror	4-6	Enabling
Cyrocooler	3-4	Enabling

Instrument	
Telescopes	4
Aperture Diameter	3.2 m
Array Length	36
Angular Resolution	50-75 milli-arcsec
Stellar Light Rejection	> 10^6
Field of View	1 to 5 arcmin
Sky Coverage	+/- 45 deg anti-sun
Wavelength Range	7-17 μ
Spectral Res.	$\lambda/\Delta\lambda = 100$
Telescope Temp	< 40 K
Detector Temp	< 6 K

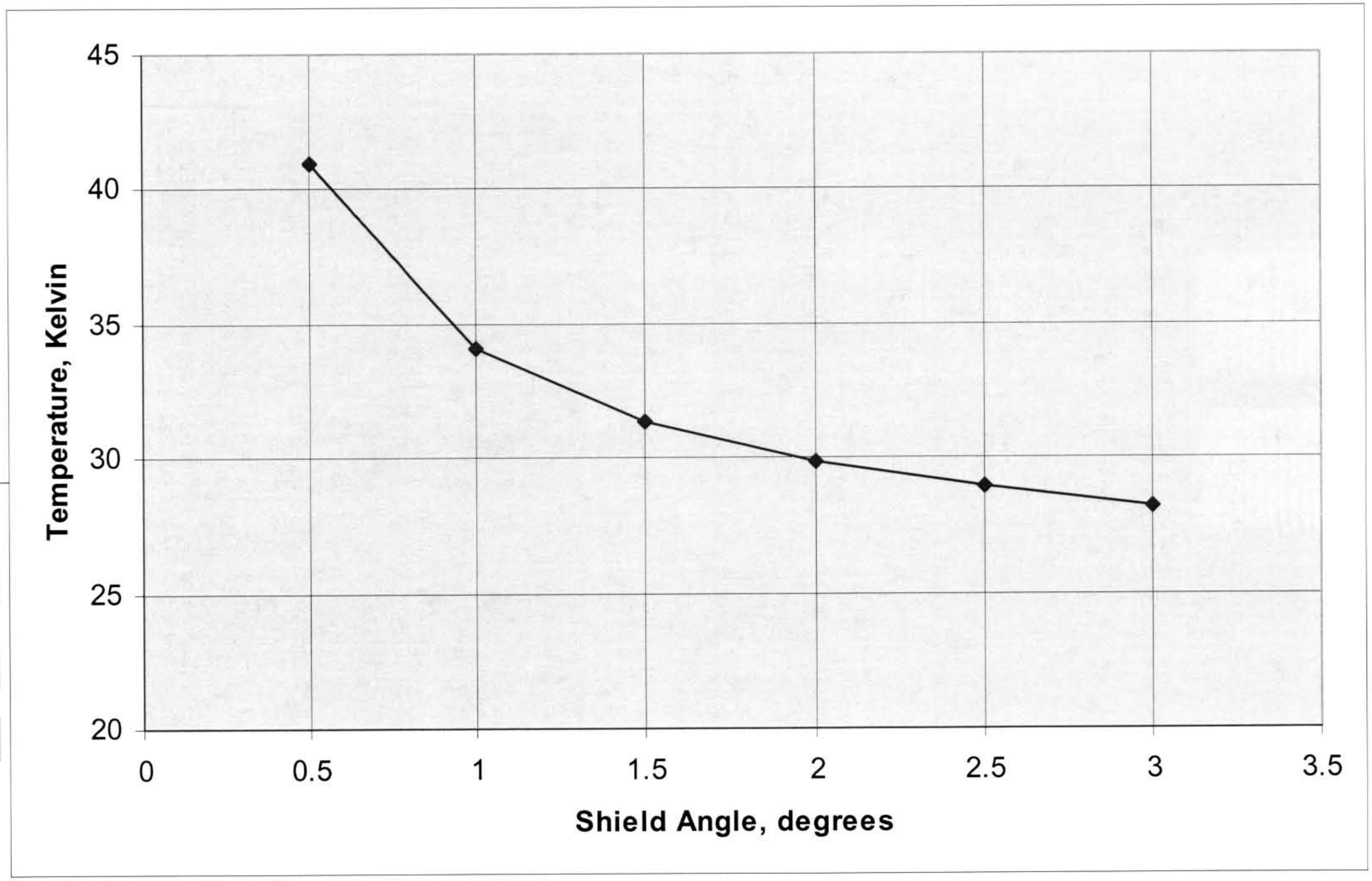
DC Power	
Predicted Max	1495 W
Margin	30%

Mass	
Collectors (4 ea.)	405 kg
Combiner	537 kg
Spacecraft	1052 kg
Truss, Etc.	1467 kg
Total Launch Mass	4679 kg
Total Margin	4725 kg

Observatory	
# of Collectors	4
Design Life	10 years
Attitude Control	3-axis
Pointing Accuracy	15 as
Pointing Knowledge	10 as
HGA Pointing	3-axis
Solar Array Pointing	3-axis
Data Downlink Rate	486 kbps
Downlink Frequency	X-band
Onboard Data Storage	1.1 Gbits
Uplink Data Rate	2000 bps
Uplink Frequency	X-band
Mission ΔV	650 m/s

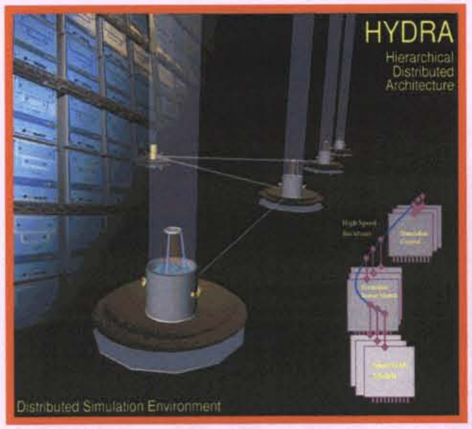
Trajectory	
C3	-0.69
ΔV (TCM's)	105 m/s
Launch Vehicle	Delta 4050H
Duration	100 days
Mission Orbit	L2 Halo

TEMPERATURE OF TOP OF SUNSHIELD VS. ANGLE BETWEEN LAYERS



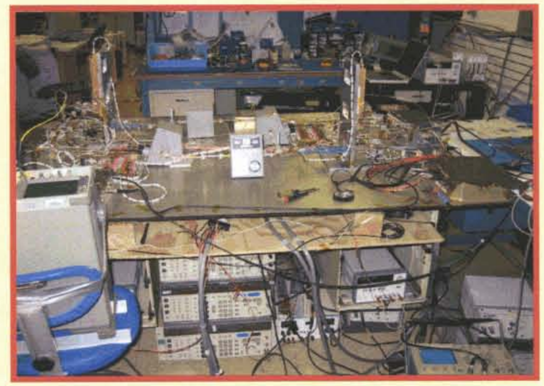
FF Technology Testbeds

Formation Algorithms & Simulation Testbed (FAST)

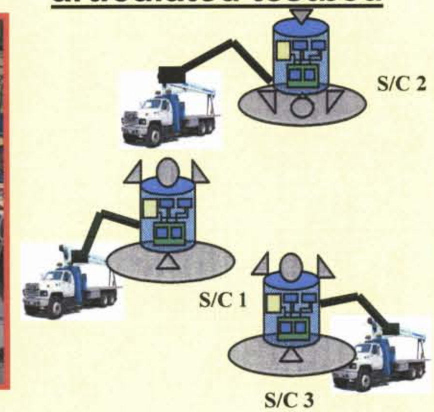


Formation Sensor Testbed (FST)

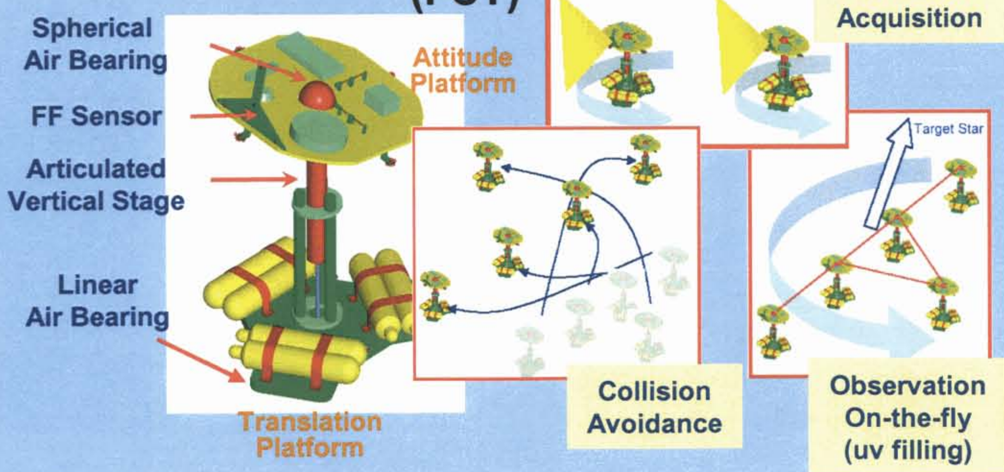
Hardware-in-the-loop testbed



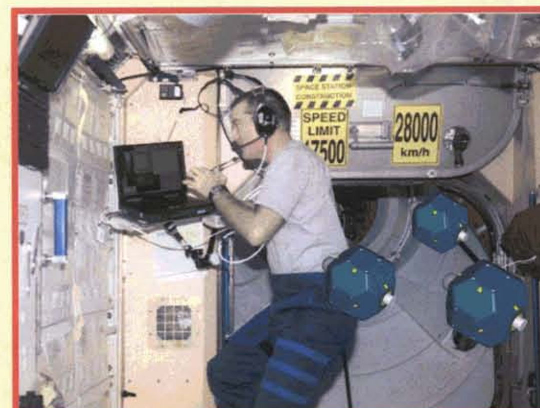
4π-steradian articulated testbed



Formation Control Testbed (FCT)



MIT SPHERES

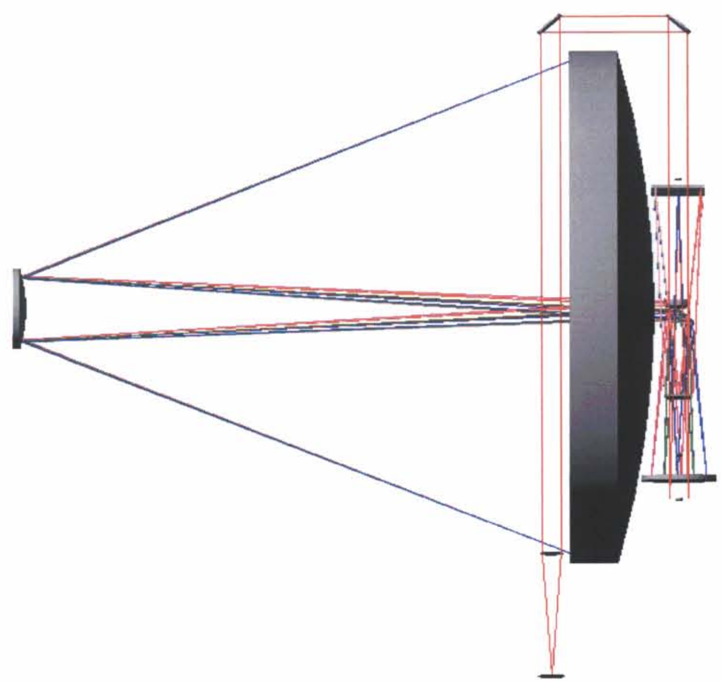


Inside International Space Station (ISS)

FFI Telescope Concept

Terrestrial Planet Finder Mission

TPF



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FFI Telescope Concept

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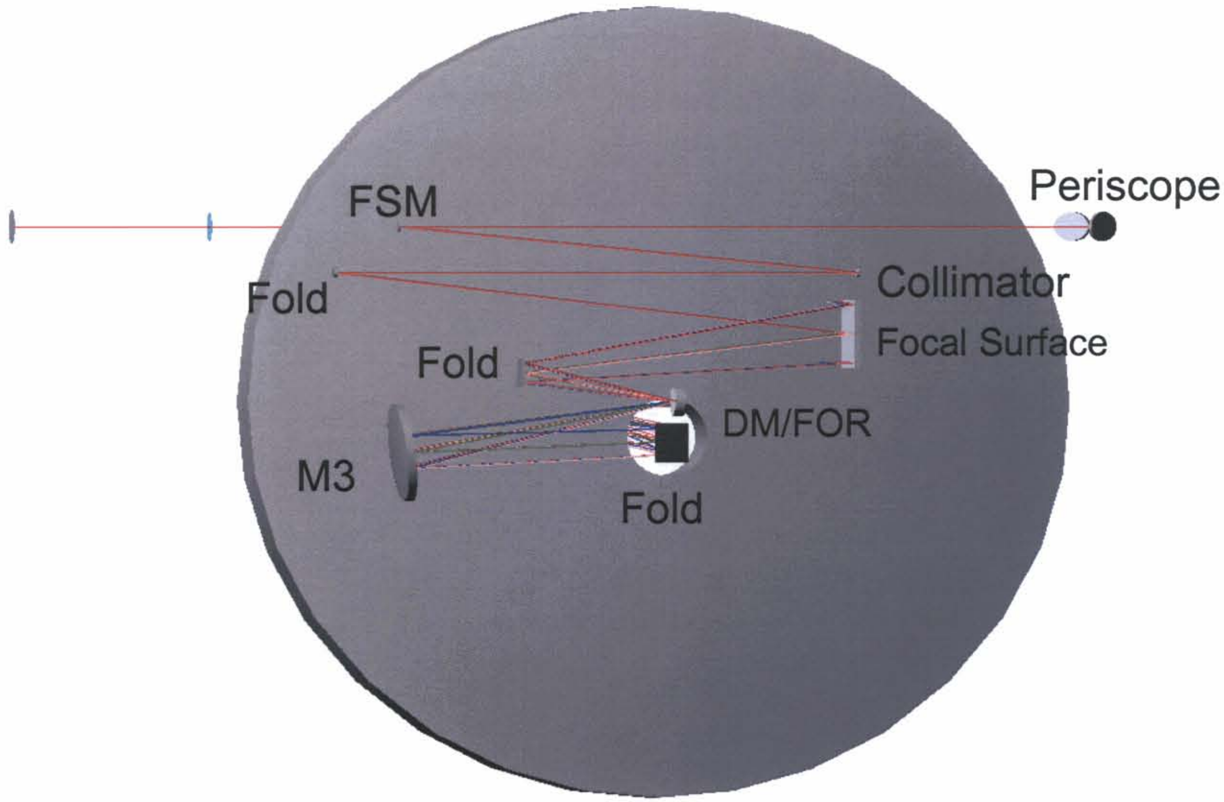


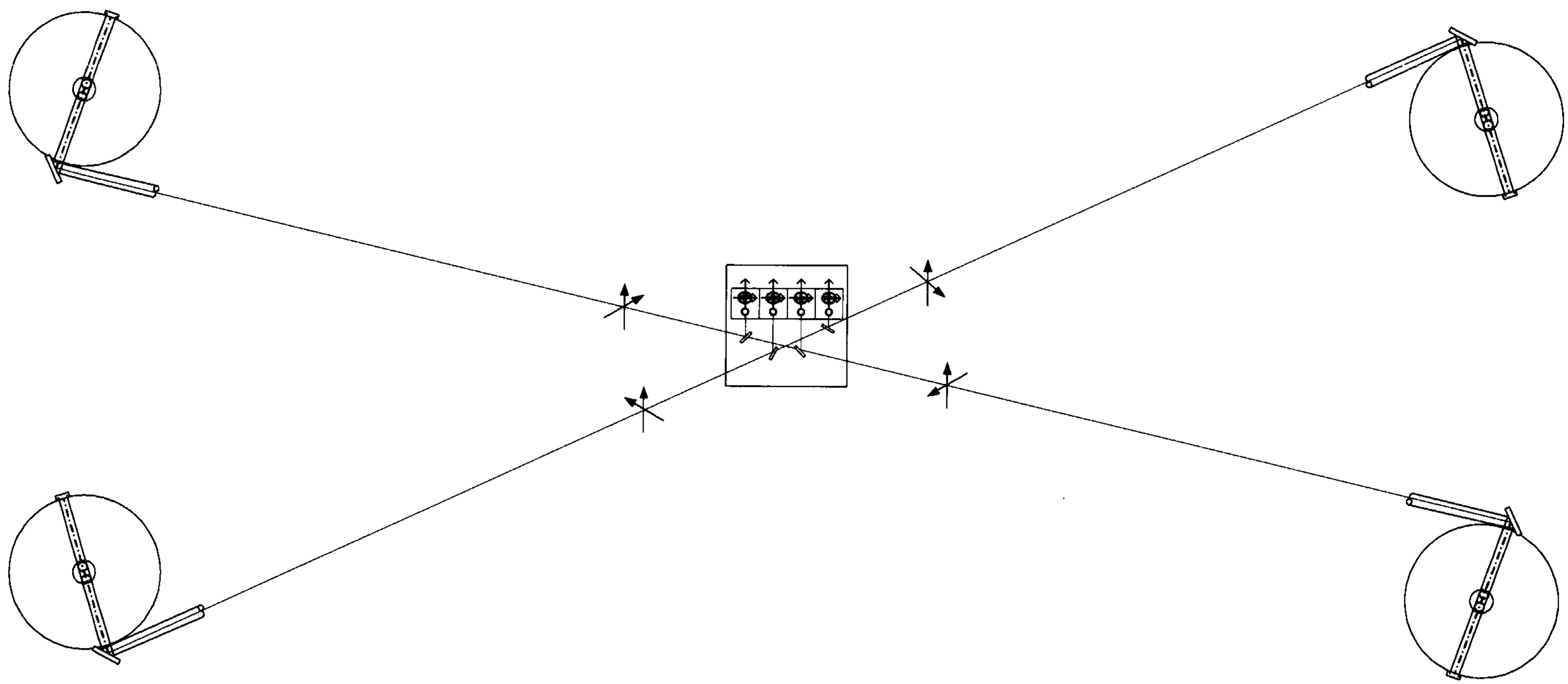
Introduction

This work is based a lot on the work performed for the SCI. The main difference between the FFI and the SCI is the lack of a truss and the distance between collectors and combiner.

The lack of a truss causes the instrument to add a sources on the collector and a camera on the combiner for use in formation acquisition/ flying and for beam shear and pointing control. It also increases the stroke of the delay line from 10 mm to 20 mm and possibly a meter. A meter should be designed into the delay for low bandwidth adjustment.

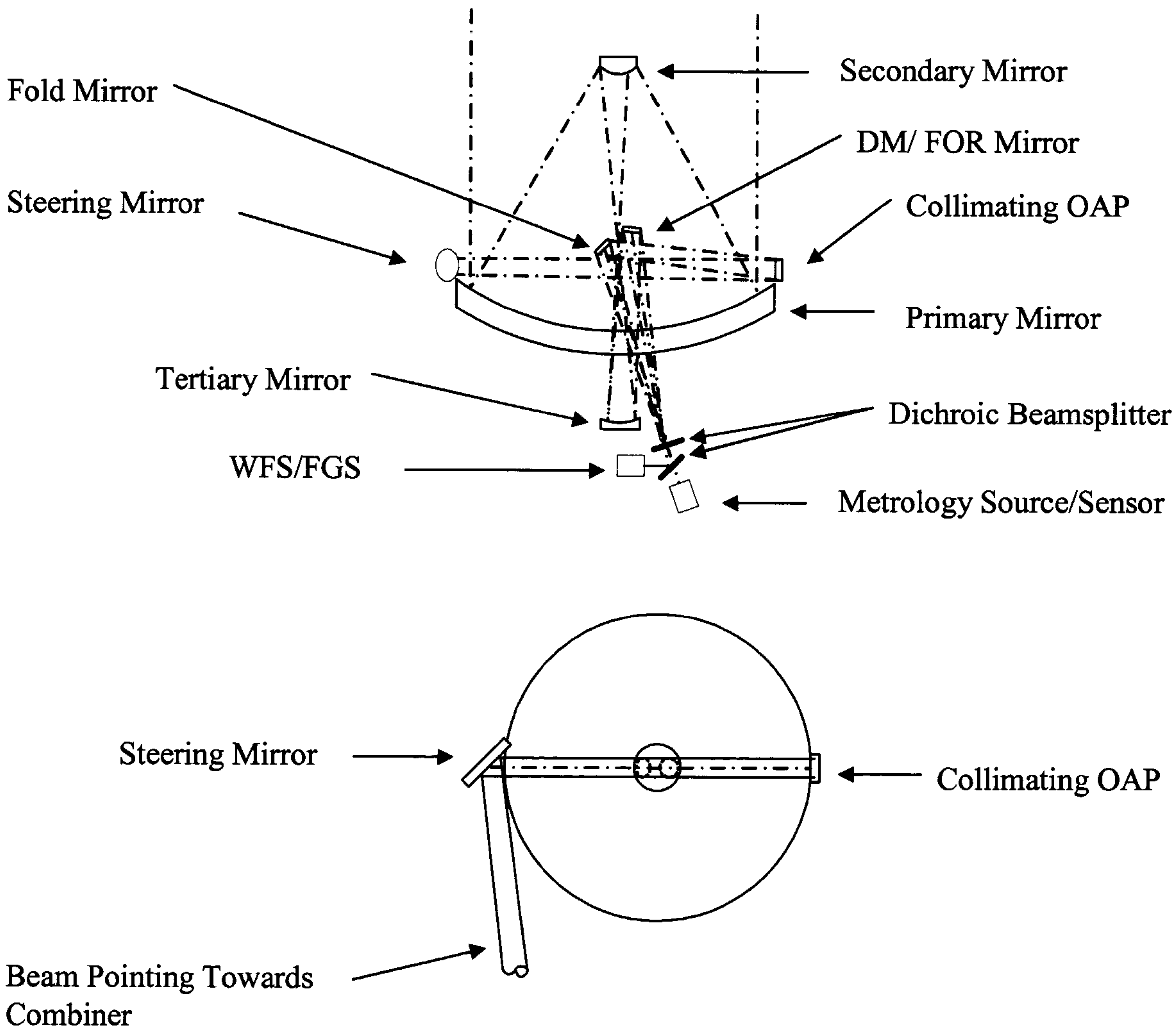
The longer separation mostly effects the beam size being relayed from the collector and combiner. The beam should be larger in diameter to account for diffraction. It may also be helpful to apodize the intensity profile of the beam. (It gets apodized in the modal filter.)

Collector and Combiner Geometry



This geometry arrangement allows all combiners to be identical. The angles of the fold mirrors in the combiner have 2 different values. The telescopes can be rotated to make the sum of the angles for all the mirror pairs to be the same. The crossed arrows are an attempt to show the orientation of the pupils coming out of the collectors and how they can be all end up aligned the same as they enter the beam reducing telescopes. This common alignment of pupils must be maintained all the way to the science detector or corrected prior to entering the MMZs. The π phase shift between 2 telescopes is obtained with dielectric phase plates and not by rotating the pupils. The advantage of this approach is that it produces grey fringes in the out-of-band wavelengths for the fringe trackers and allows for quadrature fringe tracking, which doesn't require scanning mirrors.

Side and Top View of Collector Telescope



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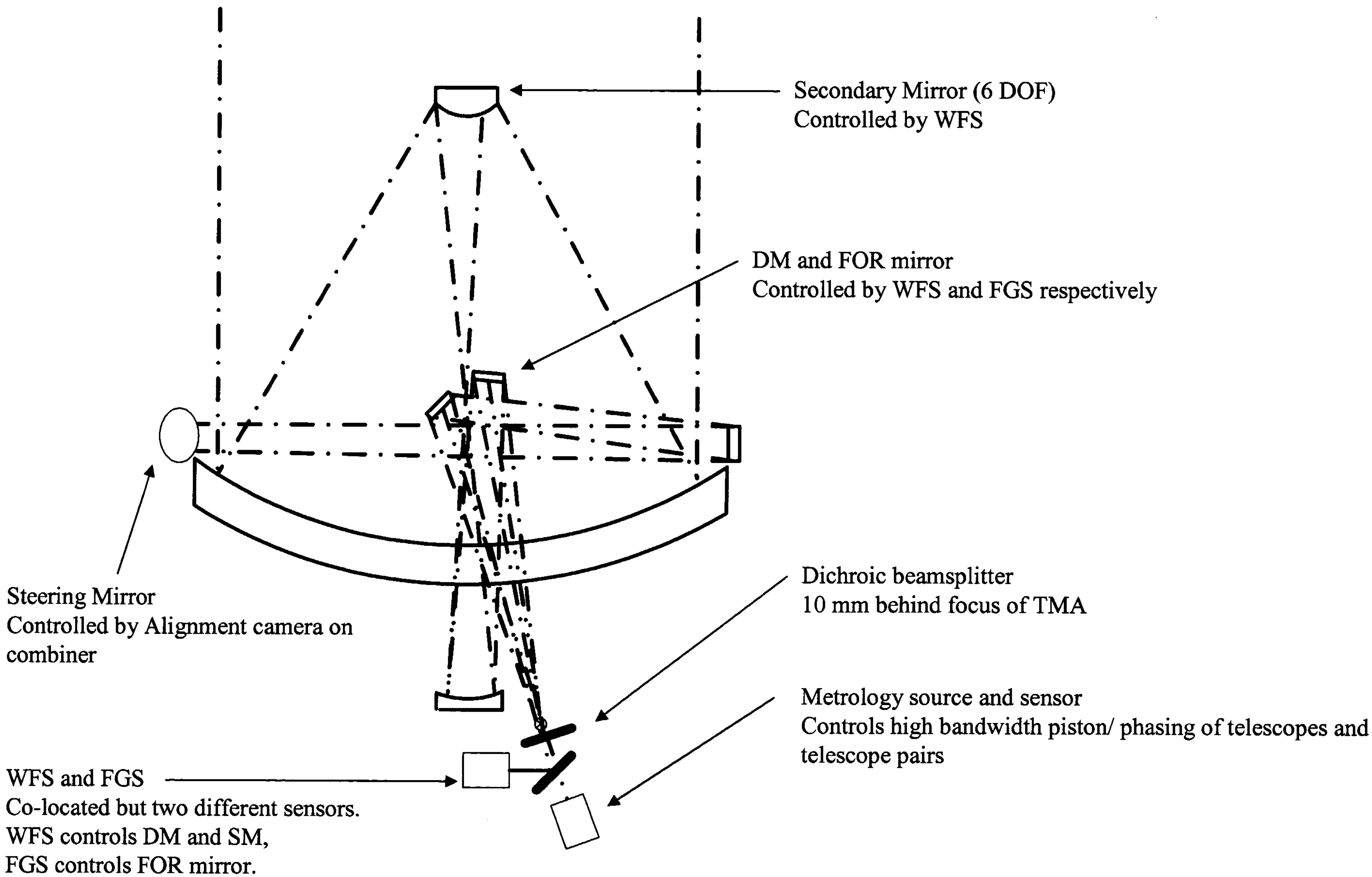
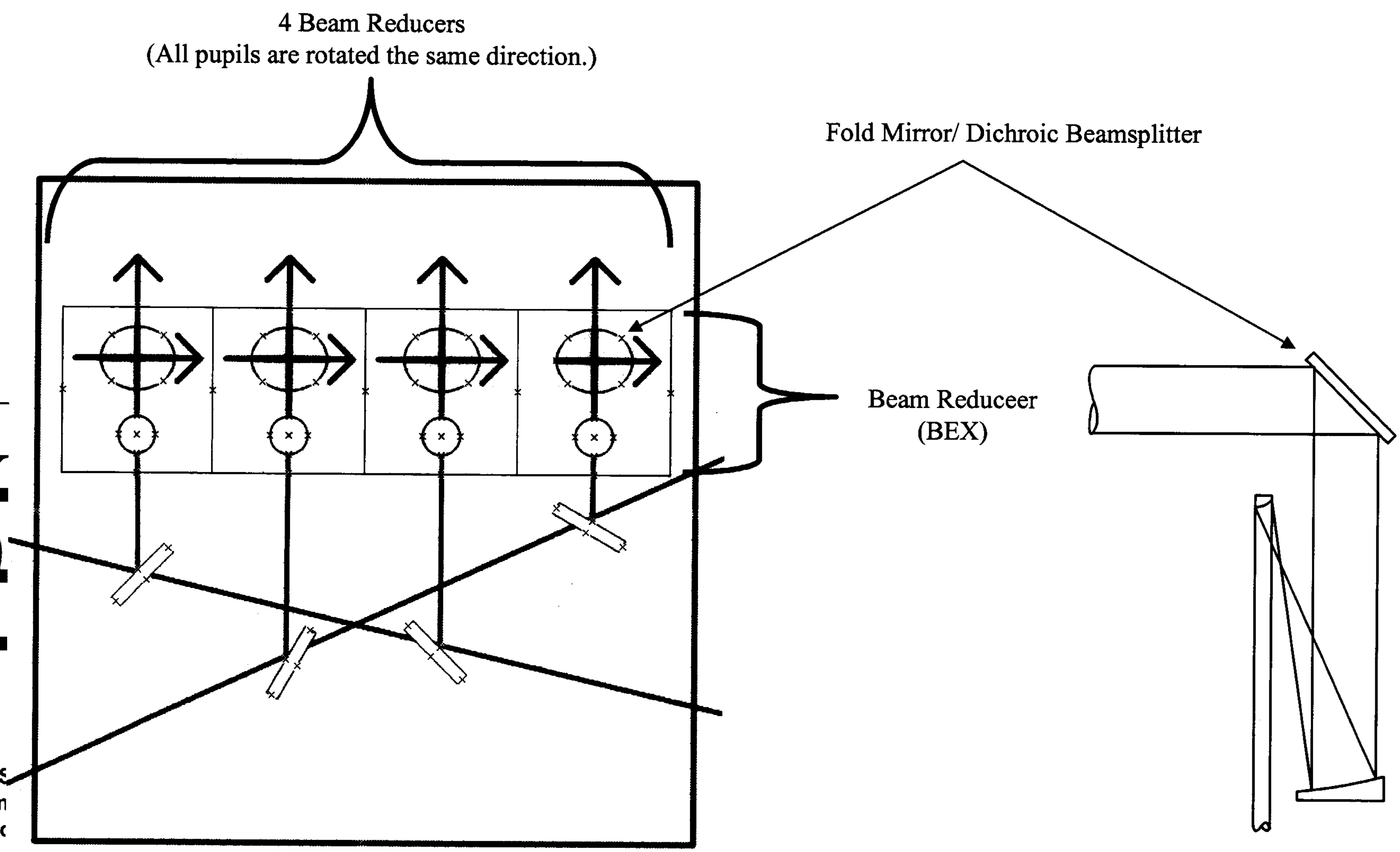
Collector Optical Layout

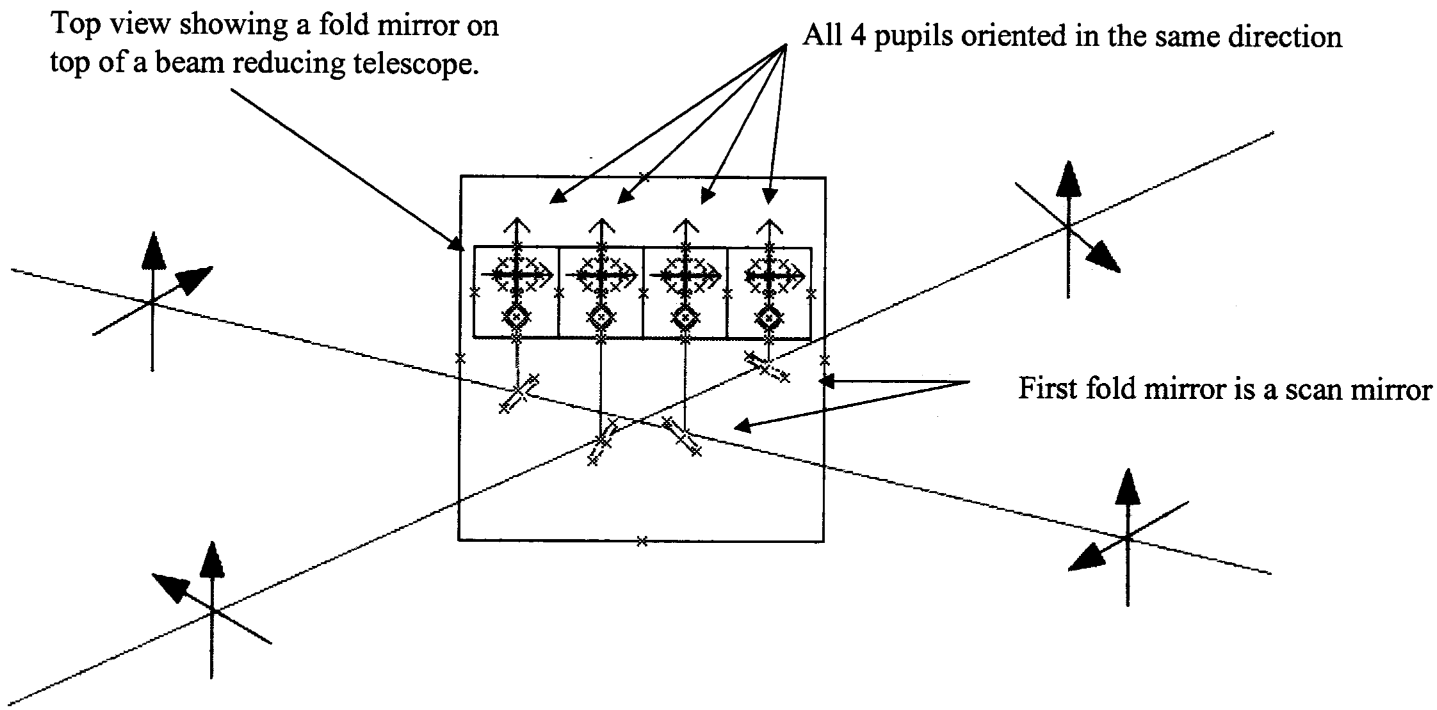


Beam Reducing Telescope



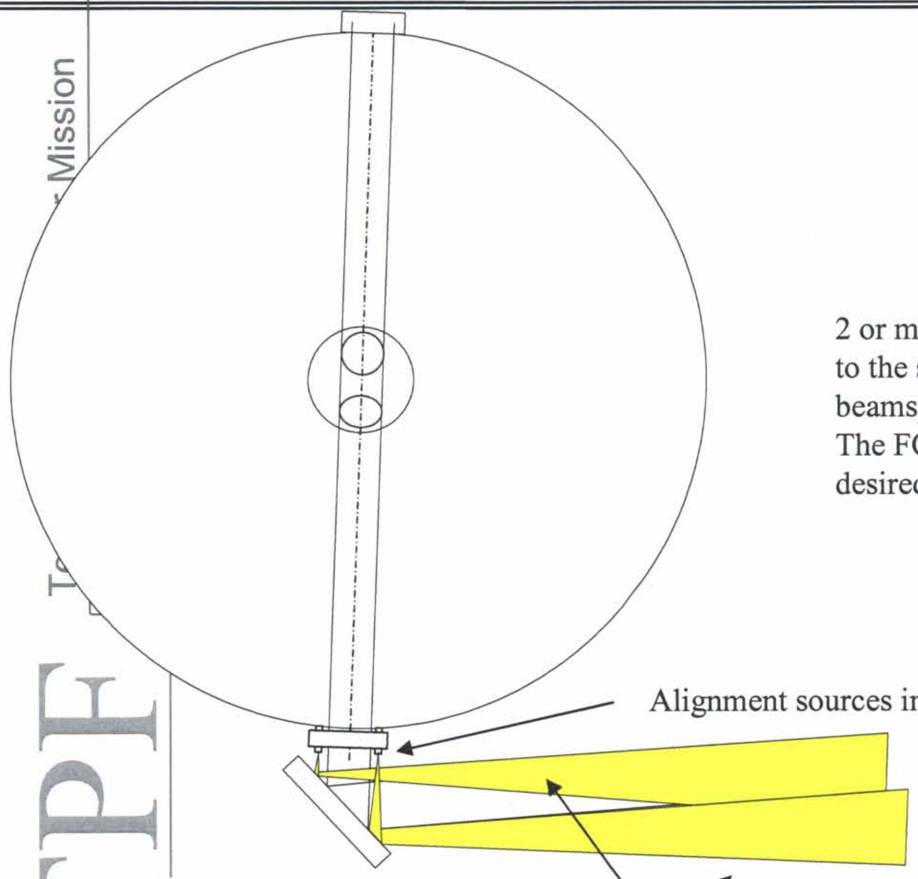
Top View of Combiner

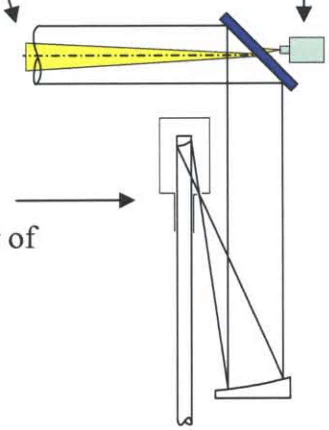
The first fold mirror reflects the beam in the plane of the collectors. The second fold mirror folds the beam 90 degrees from the plane of the collectors. This keeps all the beam apertures oriented in the same direction.



Alignment Cameras Between Collector and Combiner

2 or more sources are attached to a ring around the science beam, close to the steering mirror. An imaging camera is placed behind a dichroic beamsplitter at the first fold after the steering mirror on the combiner. The FOV of the sources and sensors are ~ 5 mrad. 2 degrees might be desired are is easily achievable.





Block Diagram of Optical System after BEX

(for 1 Telescope)

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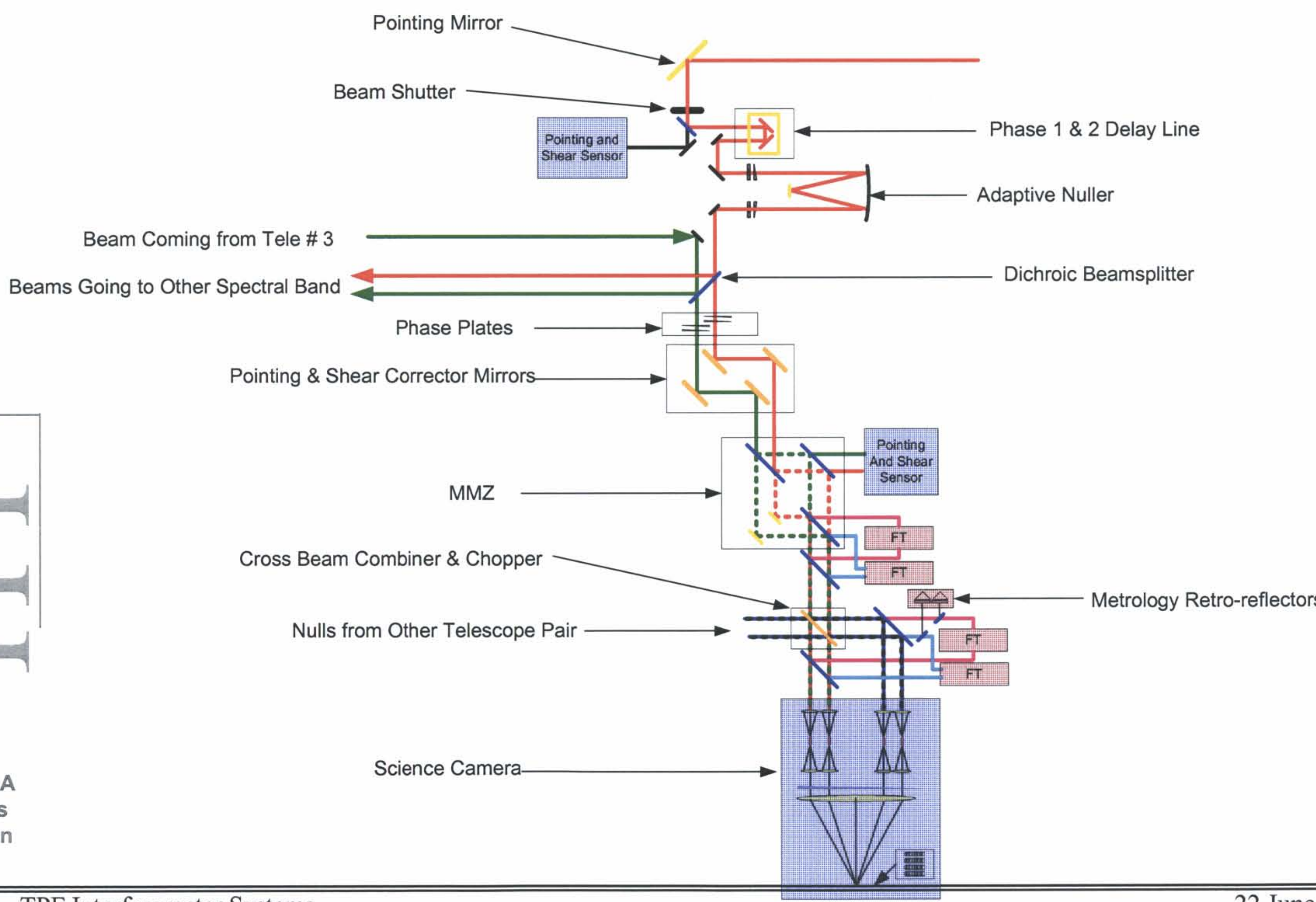

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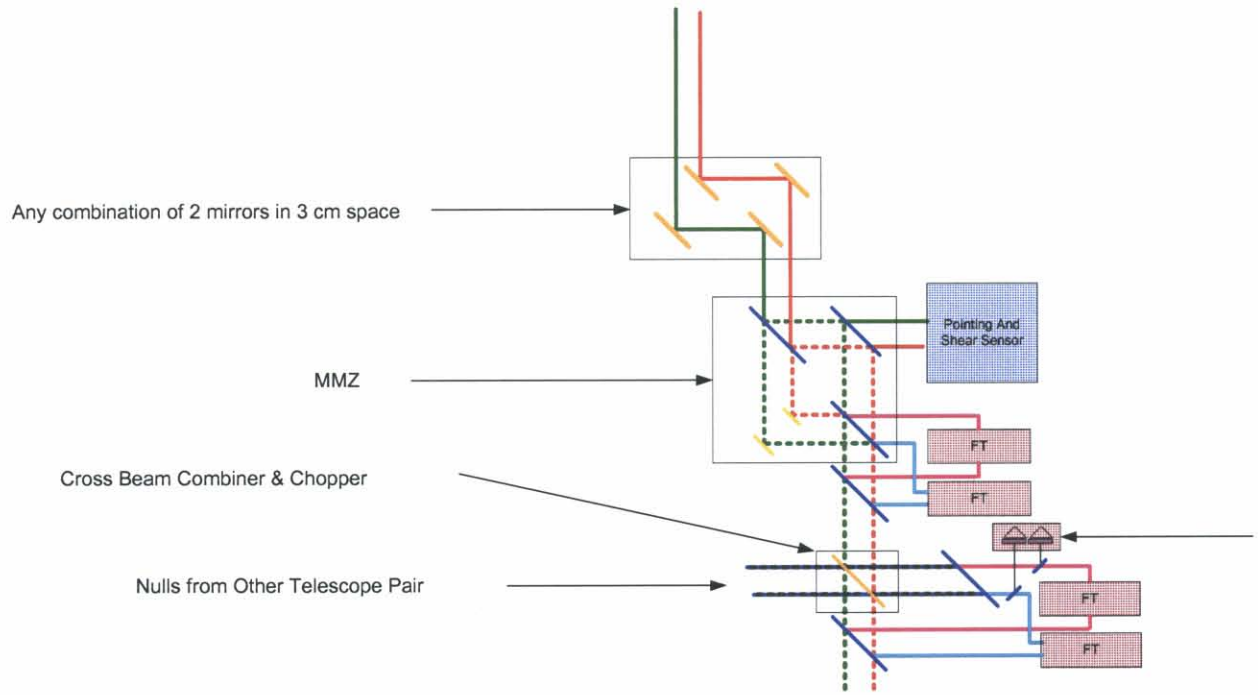
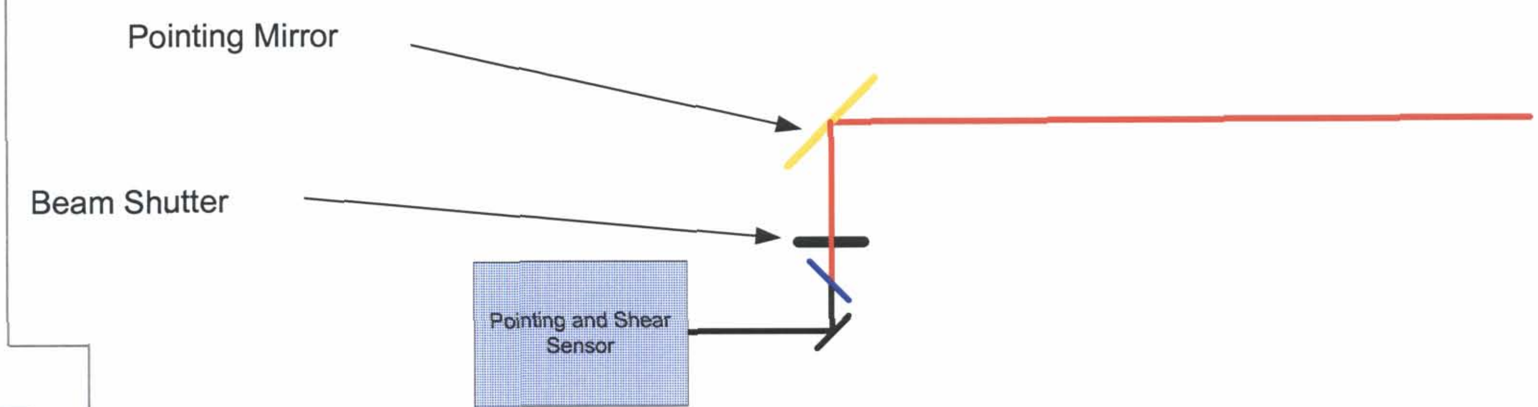
High Bandwidth Pointing/ Shear and Piston Sensors

The high bandwidth pointing/ shear sensors operate in 3 cm beam space. The shear sensor images onto the mirror that controls tilt and the tilt sensor images the far field image. Both sensors use the metrology beam. Almost any two small mirrors can be used for this function. The shear mirror has to be before the pointing mirror and both mirror have to be before the sensors.



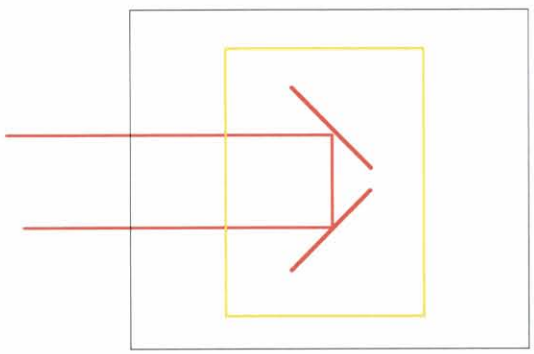
The high bandwidth piston sensors uses fringes from the metrology beams located at the metrology source on the collector and control the piston mirrors in the MMZs. The fringe sensors shown here, are low bandwidth and use wavelengths from the target star that are shorter than the bandpass of the science sensor. The phase plates are only achromatic in the bandpass of the science camera and therefore produce grey fringes in these fringe sensors. The fringe sensors off the MMZs, control the piston bias of the mirrors in the MMZs. The fringes from the 2 fringe sensors are $\pi/2$ radians apart, allowing the use of quadrature sensing. The fringe sensors off the combiner beamsplitter, equalizes the OPD between this MMZ and the other MMZ. These 2 sensors are also use out-of-band wavelengths and are $\pi/2$ radians apart.

First Pointing and Shear Sensor



This sensor controls pointing and of the beam from the telescope (collector) to the combiner. Pointing and shear control requires 2 mirrors. The first mirror (controlling beam shear) is the last steering mirror on the collector. The second mirror (controlling beam pointing) is the first big steering mirror on the combiner. The shear sensor images the metrology beam on the combiner steering mirror. The pointing sensor images the far field image of the metrology source.

Delay Lines



This delay line shows one roof mirror. The design developed for the SCI used 2 roof mirrors moving in opposite directions. This was a reaction less design that produce and OPD = 6 times the motion of one roof mirror. Moving the pair of roof mirrors has the same effect as moving a single roof mirror. (1m at 0.1 HZ.)

Large strokes at low bandwidth can be corrected for by translating the pair with a translating stage. Smaller strokes at lower bandwidths can be corrected with voice coil actuators moving the 2 roof mirrors in opposite directions. (20mm at a few Hz.) Delays at higher bandwidths are called piston errors and are controlled by the piston mirrors.

The delay line in the FFI works similar to the scan mirror (corner cube) of a Fourier Interferometer Spectrometer. In a Fourier Spectrometer, a HeNE laser is used in counting fringes to measure the relative position of the scan mirror. When the scan mirror, in one arm of the interferometer, passes through equal path length of the 2 arms, the detector will see a signal that goes to ~zero and then back up again. This is called the white light fringe. The same thing happens in the FFI, the metrology system counts fringes to measure the relative location of the delay lines. When one delay is scanned to achieve equal path length between the two telescopes, the signal will go through a null at that location. The metrology system knows where that location was so it can drive the delay line back to the null position. Using the beam blocks, the process can be repeated for each telescope, in pairs, leaving one telescope as the reference. The detector, in this case, would be the science camera.

Science Camera

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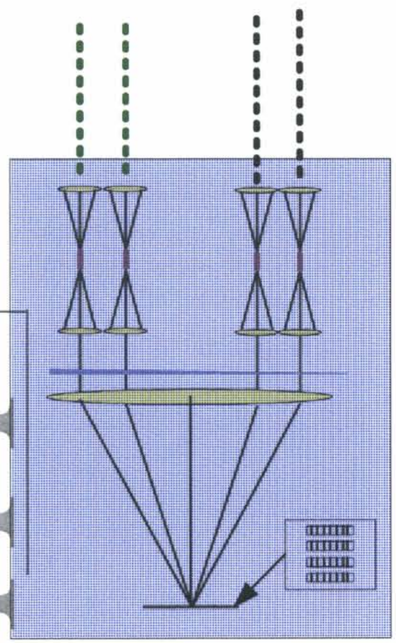

Science Camera

The main function of the science camera is to collect intensity and spectroscopy data on the target star. 2 of the nulls transmit the chopper beamsplitter and 2 are reflected off. The reflected nulls are $\pi/2$ radians out of phase with the transmitted nulls. The pair of transmitted nulls can be added, after the modal filter, to form one linear image onto the detector array. The same is true for the reflected nulls. This would yield 2 linear arrays of detectors. An alternative is to keep two arrays per pair and to use cross polarizers between them.

Shuttering the beams allows the science detector to be used for calibration of the adaptive nuller.These are the only function of the science detectors. It can consist of a 2D linear array, 2 linear arrays or 4 linear arrays. 2 linear arrays use the minimum number of detectors and should produce the best signal to noise ratio.

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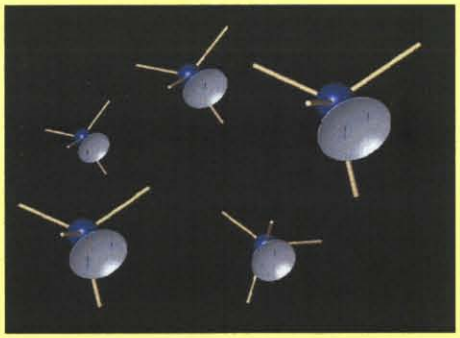
FF Technology Testbeds

Formation Interferometry Testbed (FIT)

Electromagnetic Formation Flying (EMFF)



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