Terrestrial Planet Finder Architecture Study
Preliminary Architecture Review

Ball Aerospace Team Presentation
13 December 2000
San Diego

Presentation Agenda

A: Introduction and Overview

Kilston

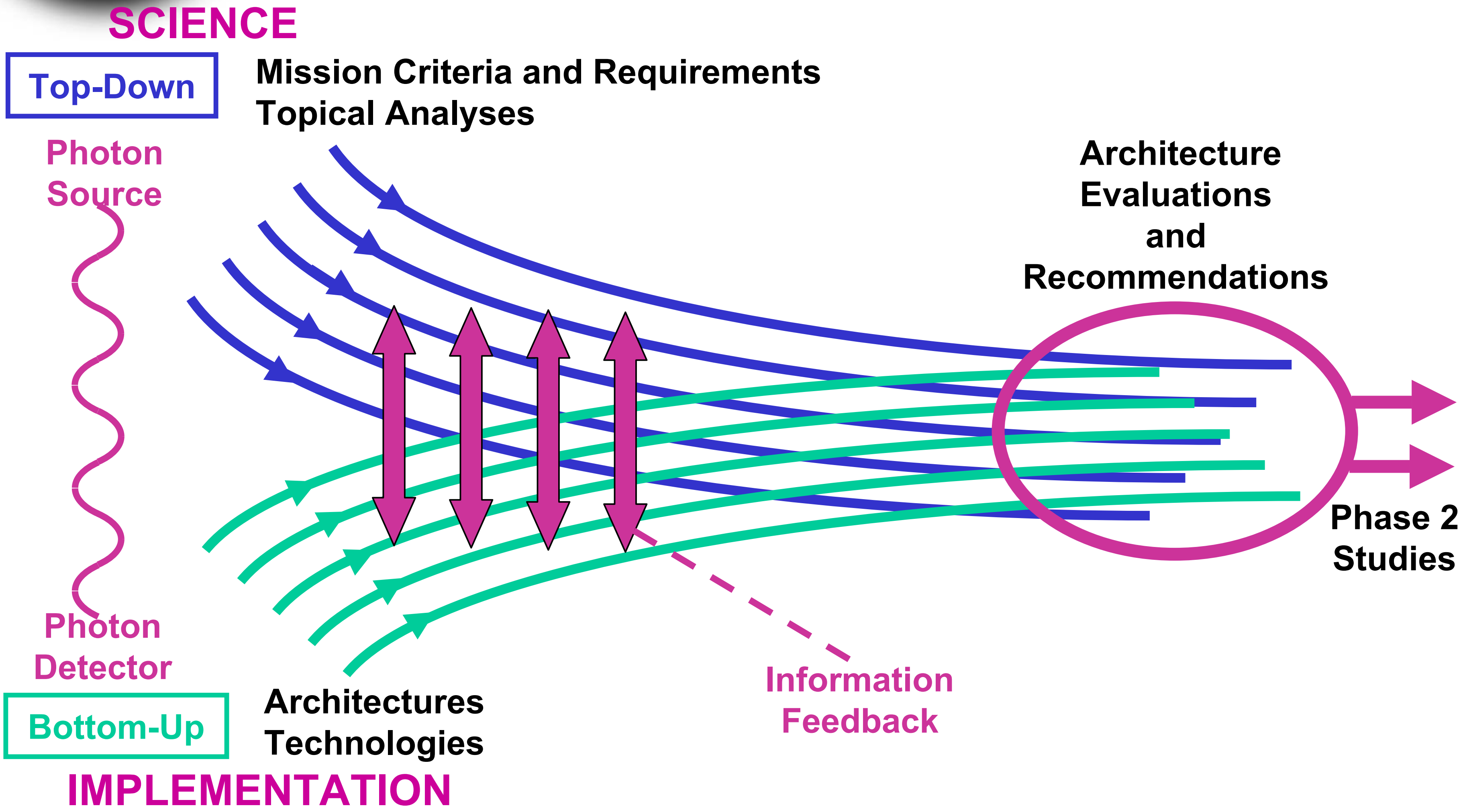
Phase 1 TPF Preliminary Architecture Study activities featured:

- A very experienced and wide-ranging team of astronomers, optics experts, and engineers
- Creative invention "covering the waterfront"
- Spirited discussion
- Critical analysis
- Careful initial evaluation

Casting (Kasting ?) the Net Broadly

http://www.photolib.noaa.gov/fish/fish1165.htm

Our PAR Defines and Ranks Architectures Based on a Top-Down/Bottom-Up Approach



SCIENCE

Top-Down

Mission Criteria and Requirements
Topical Analyses

Photon Source

Architecture Evaluations and Recommendations

Phase 2 Studies

Photon Detector

Bottom-Up

Architectures
Technologies

Information Feedback

IMPLEMENTATION

Key TPF Science Factors

Phenomenology Inputs

- Planet and star properties, contrasts, variations, backgrounds
- Detectability of biomarkers as function of wavelength and sensitivity
- Properties of astrophysical objects of interest

Science Performance Measures

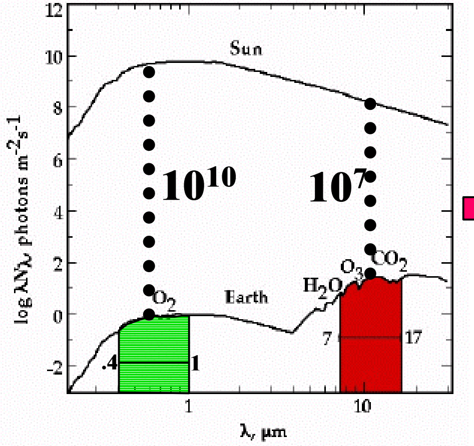
- Capture rate (science throughput) for planet detections, useful spectra
  - Capability of measuring expected planet physical and chemical properties
  - Dealing with effects of noise due to local zodi and expected exozodi
  - Minimizing false detections due to background source confusion
- Uniqueness and efficiency of capabilities for astrophysics imaging and measurements, in comparison to other space and ground systems

Key TPF Implementation Factors

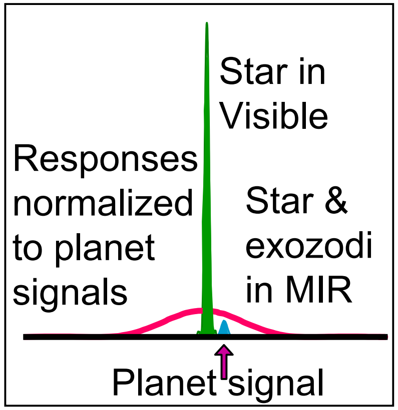
- Wavelength bands **(A key result of the Ball Team's study)
- Spatial resolution
- Size and number of collector(s), contributing to system sensitivity
- Capability to reduce starlight leakage in planet search directions
- Usable fields of view
- Robustness against contamination and other environmental concerns
- Predicted technology capabilities, readiness, and path to future missions
- Ease of launch, deployment, and operations with reliability
- Potential for servicing, upgrades, wide range of instrumentation
- Public interest and support for proposed design and predicted cost

An Observation about Wavelength

- It has become widely accepted that MIR solutions are better for TPF:
  - Because, compared to visible wavelengths, MIR offers a larger ratio of the planet light to the total starlight (the latter being a big noise source)
- More important than the starlight total brightness is:
  - How much starlight and exozodi is diffracted and scattered through the observing instrument to the detector gathering photons from the planet
- In “light” of the above, the following better defines the situation:



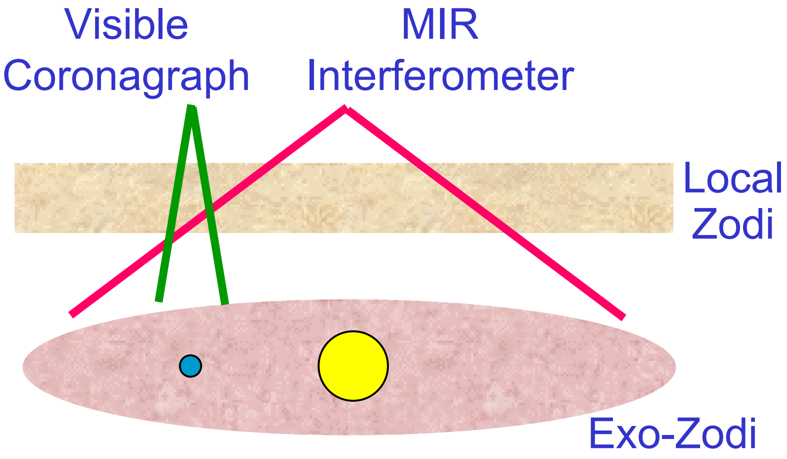
~~"IR band is 1000 times less subject to stellar noise than the Visible band"~~



Noise where planet signal is detected, from star and exozodi, may be lower for the visible, dependent also on scattering and instrument design

Main Implications of TPF Wavelength (in Order of Importance)

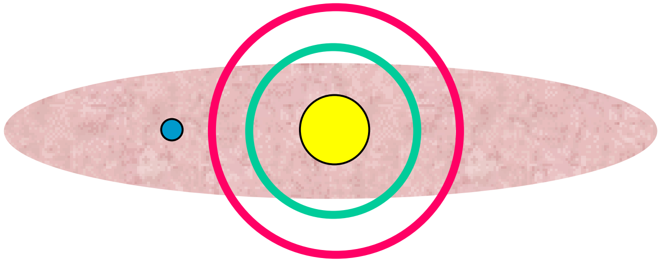
1. A visible-λ coronagraph sees less noise, more SNR



2. Good spectral biomarkers are found in both λ regions

3. Inner working distance depends on wavelength; limits are being evaluated

4. Tradeoffs involving physical properties (T, D) to be studied



Matrix of Candidate Architectures Scored Against Evaluation Criteria

Architecture:	1. 1 Spergel pupil CG-8	2. 14 Super-Darwin IF	3. 2 Masking CG-10	4. 12 Chop. L. DAC IF	5. 21 Cable-Car IF
15 - Sci.-Planet Find.	15	7	15	5	4
10 - Sci.-Planet Char.	10	9	10	7	6
25 - Sci.-Astrophys.	23	23	25	20	15
10 - Technology	10	6	6	6	6
10 - Cost	10	5	8	7	6
10 - Risk	10	6	6	6	6
10 - Reliability	10	6	8	6	6
10 - Origins Path	8	10	10	8	8
Total Score	**96**	**72**	**88**	**65**	**57**

Our Major PAR Result

- 1. A **Visible-light coronagraph** is our highest ranking TPF concept now
  - An ideal version of such an instrument provides greatest science throughput
  - Result is based on thorough exploration of TPF mission requirements and re-evaluation of SNR and integration times for different wavelength and architecture options
  - System cost could be much less than for a multi-spacecraft cryogenic nulling interferometer

- 2. An **IR interferometer** concept may or may not prove easier to build
  - Optical surface quality and scatter control might be less stringent
  - Technology challenges and development path differ from coronagraph

- Practical feasibility of either main TPF option remains in question

- Detailed modeling and design for **both** of these main design options, plus technology evolution, will permit us eventually to choose the best TPF

B: Team Members and Roles

Kilston

Science Team

Engineering Team

Management Team

Our Diverse Team of Academic, Industry, and International Partners

Princeton

Astrophysics, Wavefront Control, Metrology, Controls, Propulsion

SPACE TELESCOPE SCIENCE INSTITUTE

Science Lead, Planets, Astrophysics, Interferometry

Ball

Team Lead, ST-3 Contractor, S/C, Optical Systems, Formation Flying, Metrology, Mechanisms

Kodak

Large Optics, Integration and Test

UNIVERSITY OF FLORIDA

Mid-Wave IR Imaging and Instruments

INSTITUTE FOR ADVANCED STUDY
TRUTH BEAUTY
FOUNDED 1930

Planetary Phenomenology

🇬🇧

Arch. Concepts, Opt. Sys. Analysis

🇩🇪

High-Resolution Astrophysics

AEROJET

IR Systems, Launch, Ops, Propulsion, Detector Systems

UC SANTA CRUZ

Large Optical Systems Design

Center for Astrophysics

Interferometric Instruments

CARNEGIE INSTITUTION OF WASHINGTON
1902

Planet Theory and Observables

UCAR

Exoplanetary Systems Detection

Honeywell

S/C Controls, Formation Flying

MichiganTech

Advanced Optical Systems Design

UCSD

Arch. Concepts, Beam and Wavefront Control, Fourier Transform Spectroscopy; Instrument Engineering

Colorado
University of Colorado at Boulder

Interferometry, Metrology, Formation Flying

PENNSTATE
1855

Planet Atmospheres Chemical Evolution and Observables

L'Garde

Gossamer and Inflatable Structures

Members of the Science Team

Science Team

Member	Institution	Area of Contribution
Ron Allen	STScI	Astronomy/Interferometry
John Bally	U. of Colorado/CASA	Astronomy/Instruments
Peter Bender	U. of Colorado/JILA	Astronomy/Optics
Torsten Böker	STScI	Interferometry
Alan Boss	Carnegie Inst. of Wash.	Planetary Science
Robert Brown	STScI	Astronomy/Optics/Planets
Tim Brown	UCAR/HAO	Astronomy/Planets
Chris Burrows	UK	Optics
Webster Cash	U. of Colorado/CASA	Astronomy/Instruments
Jim Crocker	Ball	Instruments/Technology
Dennis Ebbets	Ball	Astronomy/Optics
Christ Ftaclas	Michigan Tech.	Optics
Norm Jarosik	Princeton	Astronomy/Instruments
Jim Kasting	Penn State	Planetary Science

Science Team (continued)

Member	Institution	Area of Contribution
Steve Lubow	STScI	Planets/Orbits
Dave Mozurkewich	Naval Research Labs	Optics/Interferometry
Jerry Nelson	UCSC	Optics/Instruments
Charley Noecker	Ball	Optics/Interferometry
Alan Penny	Rutherford-Appleton	Astronomy/Interferometry
Andreas Quirrenbach	UCSD	Astronomy/Interferometry
Sara Seager	Inst. for Adv. Study	Astronomy/Planets
David Spergel	Princeton	Astronomy/Instruments
Robin Stebbins	U. of Colorado/JILA	Astronomy/Instruments
Charlie Telesco	U. of Florida	IR Astronomy/Instruments
Wes Traub	Ctr. For Astrophysics	Astronomy/Instruments
Ed Turner	Princeton	Astronomy/Astrophysics

TPF
Terrestrial
Planet Finder

Engineering Team

Jim Austin	Ball	Contam.
Dave Glaister	Ball	Thermal
Ira Becker	Ball	Software
Billy Derbes	L'Garde	Inflatables
Edgar Choueiri	Princeton	Propulsion
Harvey Clouser	Aerojet	Detectors
Porter Davis	Honeywell	Struct., Contr.
William Deininger	Ball	S/C, Propuls.
Gene Dryden	Aerojet	Sys. Eng'g.
Kenny Epstein	Ball	Princip. Engr.
Homero Gutierrez	Ball	Modeling
Tim Hawarden	Edinburgh	IR, Thermal
Paul Horowitz	Harvard	Electronics
Tupper Hyde	Honeywell	Struct., Contr.
Jeremy Kasdin	Princeton	Sys. Eng'g.
Jim Leitch	Ball	Microposit.
Mike Lieber	Ball	Modeling
Brian McComas	Ball	Optics
Michael Littman	Princeton	Opt., Controls
Gary Matthews	Kodak	Optics
Richard Miles	Princeton	IF, Lasers
Dan Quenon	Honeywell	Controls
Francis Thompson	Aerojet	Sys. Eng'g.
Doug Wiemer	Ball	Attitude Contr.

Management Team

Steve Kilston	**Program Manager**
Hugh Davis	**Deputy Program Manager**
Vera Kilston	**Presentations**
Terry Lapotosky	**ITAR Regulations**
Harold Reitsema	**Executive Liaison**
Doak Woodruff	**Contracts**
Lisa Yedo	**Finance**

C: Study Process

Brown

Study Approach
Discovery, Qualification, and Organization of Architectures
Architecture Families

Ball Approach to Preliminary Architecture Review (PAR)

- Architectures
  - Identify solutions and organize into families
  - Appoint "captains" to develop and advocate architecture options
- Criteria
  - Develop Design Reference Program, flow down its requirements
  - Analyze the criteria to identify issues with performance and technology
- Studies
  - Target topical studies at the issues
- Evaluation
  - Use studies to evaluate architectures via criteria

Discovery, Qualification, and Organization of Architectures

- Gather existing concepts
  - Inherit from proposals, literature and reports

- Invent new concepts
  - It's all there in “Born & Wolf” !

- Qualify concepts
  - Must detect ”Earth" around ”Sun" at about 30 pc
  - Must take spectrum of “Earth” around “Sun” at about 15 pc

- Organize concepts into "architecture families"
  - ”Reflected-light", ”Emitted-light”, ”Diversity"

Architecture Families

Reflected-Light (UV/Vis./NIR) Architectures (e.g., mask coronagraph)

1. Usually one large single-aperture telescope with multiple-instrument focal plane
2. Diffraction-limited performance from UV to NIR over large FOV
3. Uncooled optics and non-cryo detectors
4. Planet-finder instrument contains variety of Fourier star-blocking options
5. Astrophysics instrumentation shares focal plane

Emitted-Light (Thermal MIR) Architectures (e.g., Darwin interferometer)

1. Multiple light-collectors plus combiner form dilute-aperture system
2. FOV limited by baseline and Airy disk of individual collector telescopes
3. Cooled optics and cryo detectors
4. Telescope beams combined, with achromatic nulling of starlight
5. Additional astrophysics instrumentation is difficult to incorporate

“Diversity” Architectures

1. Variety of schemes to gather information useful to TPF mission development

D: Key Evaluation Issues

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The Seven Architecture Evaluation Criteria
Scoring for Architecture Families

The Seven TPF Architecture Evaluation Criteria

- #1: Sensitivity in finding and characterizing exoplanets
- #2: Richness of astrophysical science opportunities
- #3: Technology development needed
- #4: Life cycle costs
- #5: Risk of cost, technology, schedule, on-orbit failures
- #6: Reliability and robustness
- #7: Alignment with the technology path to future exoplanet-study missions

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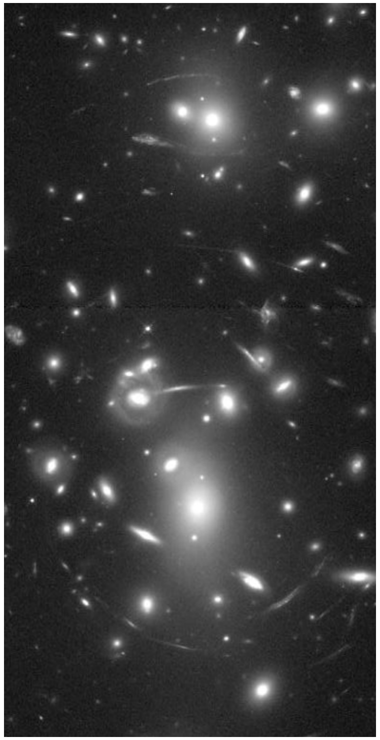
- We analyze each criterion to identify issues
  - Requirements and constraints that must be met
  - Factors related to “better” to prioritize qualifying architectures
  - Logic for ultimate scoring and overall prioritization
- At PAR time, we have a preliminary framework for scoring
  - Sufficient to guide key topical studies
  - Sufficient to illustrate the value and integrity of the criteria
  - Sufficient to feel confident about our preliminary conclusions

#1: Sensitivity in Finding and Characterizing Exoplanets

- The TPF Science Working Group provided our main science requirement in a Design Reference Program (DRP)
  - "TPF must detect radiation from any Earth-like planets in the habitable zones surrounding ~150 solar type (spectral types F, G, and K) stars. TPF must: 1) characterize the orbital and physical properties of all detected planets to assess their habitability; and 2) characterize the atmospheres and search for potential biomarkers among the brightest candidates for Earth-like planets."
- For exoplanets, "better" science performance means
  - More stars surveyed and more planets characterized
  - Planets better characterized and interpreted
- Other requirements of the DRP
  - A broader framework that includes the properties of all planetary system constituents, e.g., both gas giant and terrestrial planets, and debris disks
    - The very first question to ask after finding an Earth-like planet at 1 AU is WHAT <u>ELSE</u> IS THERE?

#2: Richness of Astrophysical Science Opportunities

- Astrophysics observations with the chosen TPF architecture should collect significant data not obtainable with any other instrument operational before or at the time of the mission



- “Better” factors
  - Wavelengths not visible with other instruments
  - High sensitivity to faint signals, especially close to noise or confusion sources
  - Response stability to permit detection of changes
  - Spatial resolutions beyond those of other instruments
  - Capability of hosting multiple different science instruments
  - More observations possible
  - Wider community served by unique capabilities
- Other astrophysics criteria
  - Ability to view whole sky
  - Ability to respond quickly to observe phenomena newly found by other systems

#3: Technology Development Needed

- Technology for any TPF architecture will be complex and contain components not currently available or proven in space
  - It is vital to find a credible path to develop new technology for TPF
  - We have based our selected architecture ideas on technology appearing to have a chance of being ready in the time frame needed for TPF

- “Better” factors (discriminators)
  - Fewer "tall poles"
  - Greater technological inheritance
  - Easier tests of technological readiness
  - Number of critical path technology items (that is, how is development of key technology going to drive schedule and cost?)
  - Are there viable alternatives should technology development falter or lag?
  - Are flight demonstration programs required to verify technology and how many?

#4: Life-cycle Costs

- Money is an object
  - TPF funding is not likely to support much more than twice the NGST cost level
  - The greatest fraction of TPF cost is expected to reside in the space segment

- “Better” factors
  - Lower system cost
  - Lower operating costs
  - Lower opportunity costs associated with delay
  - Lower technology-development costs
  - Lower time costs per target observed
  - Lower overall system cost per Earth-like planet found and characterized

#5: Risk of Cost, Technology, Schedule, On-orbit Failures

- Risk elements must be minimized, and balanced against the advantages promised by innovative designs based on new concepts and technologies
  - TPF begins as a high-risk system, and a major goal is to find and follow all paths needed to reduce its risks to tolerable levels
- "Better" factors
  - Greater similarity to previous development projects
  - Are descoping options available that don't dramatically alter mission goals?
  - Less technology development needed
  - Existence of viable alternatives (backup plans)
  - Complexity of test and verification. Can it be verified on the ground?
  - Multiple on-orbit approaches/instrumentation as backup
  - Contamination and other environmental risks
  - Is on-orbit repair/recovery possible?

#6: Reliability and Robustness

- TPF reliability will be founded on sound analysis, modeling, and testing of all system elements
- “Better” reliability factors
  - Fewer parts and components
  - Level of redundancy
  - Proven rad-hard and space-qualified parts
  - Increased analysis and system end-to-end test opportunities
  - Resistance of optical and thermal subsystems to contamination degradation
- “Better” robustness factors
  - Design margins relative to performance requirements
    - Fuel reserves
  - Superior resilience to elevated exozodi
  - Superior resilience to confusion sources
  - Ability to recover science in the event of on-orbit failures
  - Resilience to environment (radiation, micrometeoroids, etc.)
  - Descopes

#7: Alignment with the Technology Path to Future Exoplanet-study Missions

- Technologies the TPF program develops and utilizes must be on a path to the future planet characterization missions projected by NASA
- “Better” technology path factors
  - Technologies already identified as characteristics of the future missions
  - Technologies beyond what are already being developed on other programs
  - Technologies likely to fit within cost and schedule allocations
- Characteristics of expected future missions

Life Finder – High-SNR spectroscopy
Visible or MIR wavelength coverage
Large apertures (25 m)
Nulling

Planet Imager – Super-high resolution and radiometric sensitivity
Large baseline – Probably interferometer with formation flying
Visible wavelength coverage
Very large apertures (40 m)
Nulling

The Two Main Architecture Families vs. the 7 Criteria

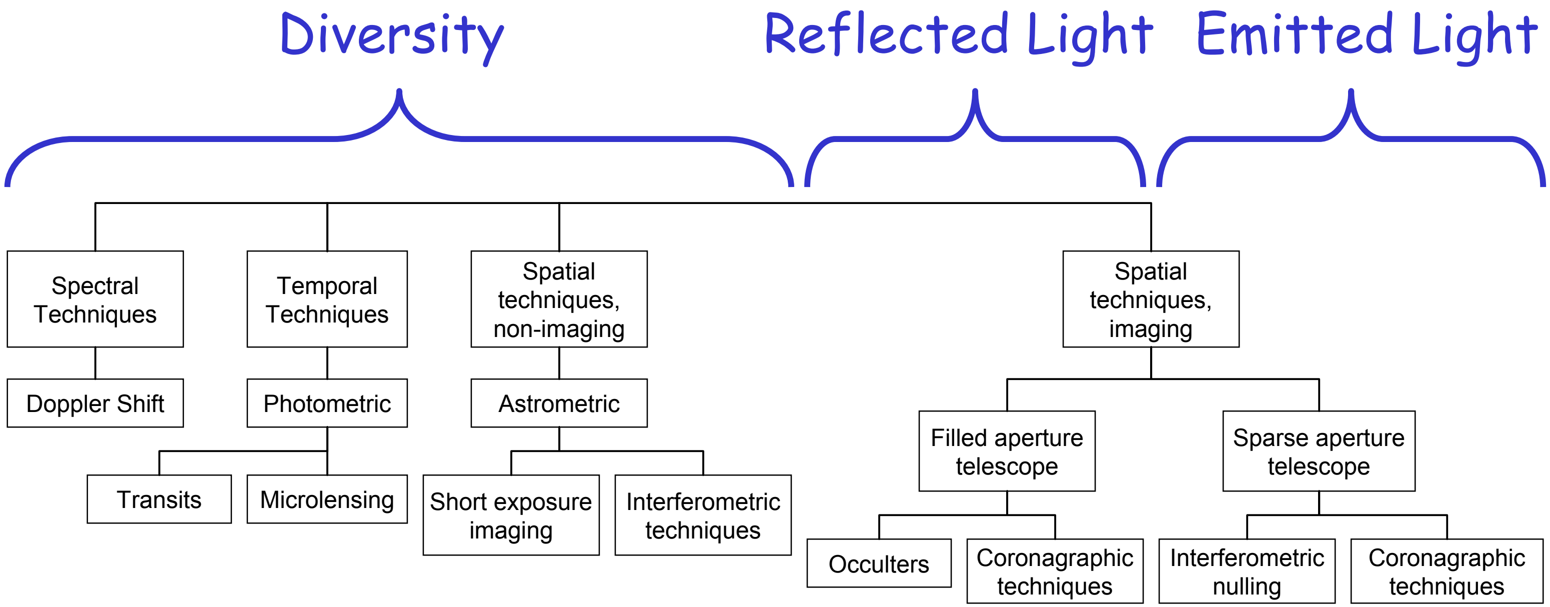
Architecture Family Criteria	Emitted Light – MIR (Interferometers)	Reflected Light – Vis./NIR (Coronagraphs)
1. Sci. – Exoplanets		√
2. Sci. – Astrophysics	√	√
3. Technology		√
4. Cost		√
5. Risk		√
6. Reliability		√
7. Origins Future Path	√	√

Check = Preferred or Equal

E: Candidate Architecture Descriptions

Spergel, Noecker, Kilston

30 options in 3 Families



Diversity

Reflected Light

Emitted Light

- Spectral Techniques
  - Doppler Shift
- Temporal Techniques
  - Photometric
    - Transits
    - Microlensing
- Spatial techniques, non-imaging
  - Astrometric
    - Short exposure imaging
    - Interferometric techniques
- Spatial techniques, imaging
  - Filled aperture telescope
    - Occulters
    - Coronagraphic techniques
  - Sparse aperture telescope
    - Interferometric nulling
    - Coronagraphic techniques

Reflected-Light (Visible/NIR) Candidates

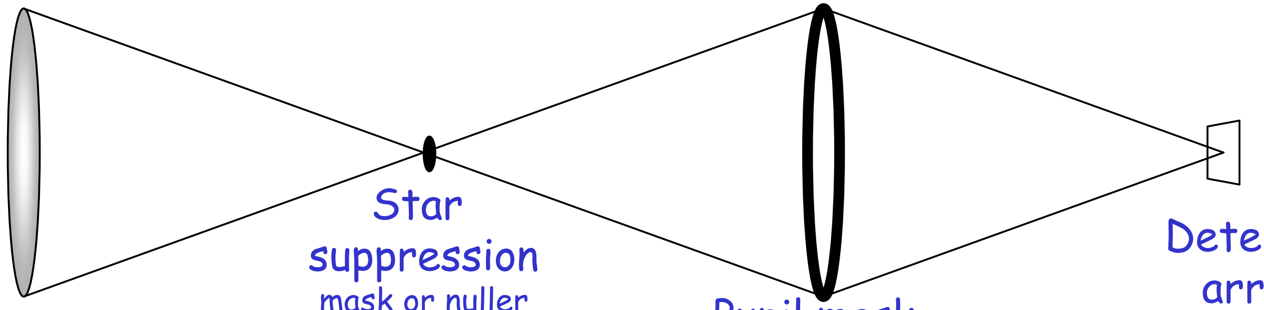
No.	Candidate	Captain(s)
1	**Spergel variable-pupil coronagraph**	Spergel
2	**Masking coronagraph**	Burrows
3	Nulling coronagraph	Boeker
4	Focal plane phase mask	Ftaclas
5	Microtube block	Kilston/Ftaclas
–	"Filter-wheel" coronagraph	Burrows
–	Coronagraph + outriggers	Penny
6	Occulting Screens	Boss
7	Spergel pinhole screen	Noecker

Performance Characteristics of Reflected-Light Candidates

#1 Planet Finding and Characterization	
Virtues for Planet Finding:	Direct imaging Insensitive to exo-zodi and background confusion All wavelengths of planet light hit the same CCD pixel
Virtues for Planet Characterization:	Good theoretical integration times; no need to re-position Strong biomarkers, including chlorophyll
Weaknesses:	Primary mirror size needed to reach small inner working angles Spectrum contamination by stellar leakage
#2 Astrophysics	
Virtues:	Direct imaging at ~4x HST resolution Different bands from NGST
Weaknesses:	Doesn’t meet 0.75 mas resolution goal
#7 Future Missions Planet Imager may use coronagraphs to isolate planet light for synthesis imaging	
Virtues:	All wavelengths of planet light at once
Weaknesses:	Speckle complicates visibility calibration

Common Characteristics of Reflected-Light Candidates

- Imaging system ⇒ SNR in planet pixel depends on backgrounds in that pixel, not in the pixel where the star is/would be
  - Widely cited 10^{10} flux ratio is not directly relevant for SNR
- Low exozodi-to-planet signal ratio in one pixel ⇒ robust to high exozodi levels
- Solutions differ in how they suppress stray starlight at the planet's pixel
  - a) Achromatic schemes that work everywhere outside a characteristic radius
  - b) Achromatic schemes that work along a narrow cone (or line)
  - c) Wavelength dependent schemes (doing one wavelength at a time is too inefficient)



Star suppression
mask or nuller

Detector array

Telescope
novel shapes

Pupil mask
Suppresses diffraction from the rim
Lyot stop/novel shapes

Coronagraph Implementation

- Strategies for scattered light
  - High-performance wavefront correction
    - Deformable mirror, typically 100x100 actuators
    - Set-and-forget, updated periodically (hourly? daily?)
    - Proven algorithms to find the right actuator positions on orbit
  - Lyot stop suppresses stray light arising from diffraction at aperture rim
    - Suppresses familiar θ^3 wings of Bessel function
    - The rim can be designed to suppress its own diffraction (Spergel pupil)
- Spectrometer for planet characterization
  - Can also accommodate other instruments on-board
- Angular resolution depends on primary mirror diameter
  - Details of star suppression affect this relationship
  - Could add cost to reach inner Habitable Zone (HZ) on all members of a large sample of stars

Candidate #1 – Spergel Variable-Pupil Coronagraph *(***Top 5***)*

Description: Visible light coronagraph on a single spacecraft, novel apodized aperture to suppress point-spread function (PSF) along one direction

Virtue: Tailored for quickest attenuation of wings.

Weakness: Elongated ends use aperture area inefficiently. Rotation needed to sweep "clean wedge" around star

Wavelength: 0.3 - 2.3 μm

Spectral resolution: 20 - 100

Optical shape/area: 40 sq m

Nulling/blocking: Focal plane mask

SNR and Msmt limit: 5 in 3 hrs (@ R=3)

Rejection of backgrounds: Confusion 0.01 obj./as^2; Imaging: exozodi-insensitive

Temporal resolution: Hours

Orbit: L2, Earth trailing, Jupiter, Princeton

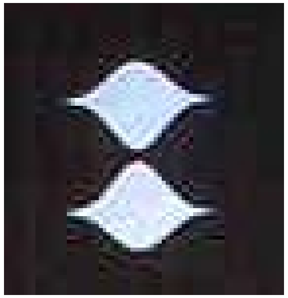
Sky coverage: Solar exclusion >60 deg

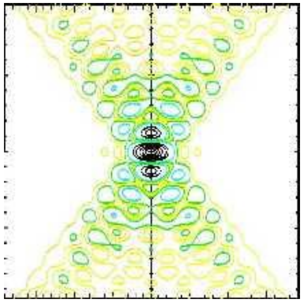
Mission thruput/timelines: One detection in 6 hrs

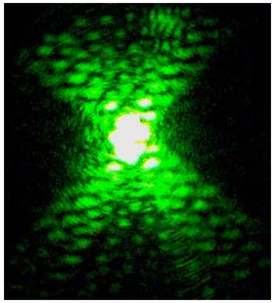
Robustness: Less vulnerable to exo-zodi, limited against distant stars with small planet separation

Astrophysics: Many objects visible at ~50 mas resolution

Future Missions: Same as other coronagraphs


Spergel pupil


PSF (theor.)


1st Lab Demo

Candidate #2 – Masking Coronagraph *(***Top 5***)*

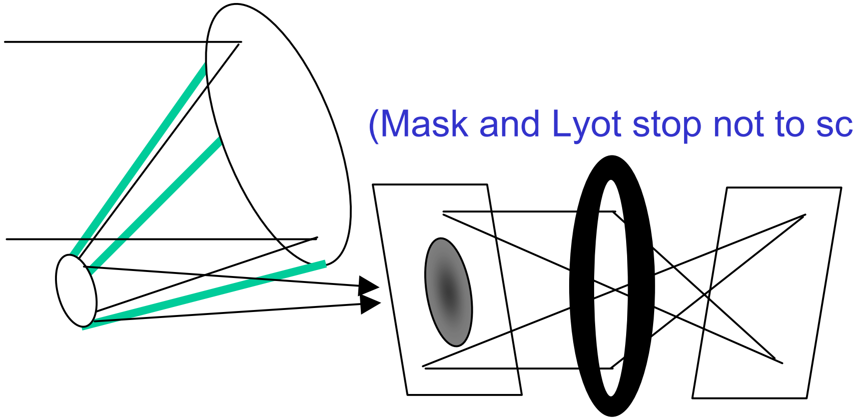
Description: Telescope with focal plane field stop (e.g., Gaussian mask) and Lyot stop in the re-imaged pupil plane

Virtues and Weaknesses: As for whole family (this is classic version of the family)

Wavelength: 0.3 - 2.3 µm
Spectral resolution: 20 - 200
Optical shape/area: Circular/50 m^2
Nulling/blocking: Gaussian field mask
SNR and Msmt limit: 5 in 3 hrs (@ R=3)
Rejection of backgrounds: Confusion 0.01 obj./as^2; Imaging: exozodi-insensitive

Temporal resolution: Hours
Orbit: L2 Earth trailing, Jupiter, Princeton
Sky coverage: Solar exclusion >60 deg
Mission thruput/timelines: One det. in 6 hrs
Robustness: Less vulnerable to exo-zodi

Astrophysics: Different masks can be available and inserted appropriate to target object



(Mask and Lyot stop not to scale)

Candidate #3 – Nulling Coronagraph *(Good)*

Description/Approach: Telescope with cats-eye or rooftop rotation-shearing nulling interferometer (used as a coronagraphic instrument)

Virtues: Ability to detect planets within the first few Airy rings

Weaknesses: Planet image in 2 spots (image doubling); dispersive elements; tight pointing

Wavelength: 0.3 - 2.0 μm, to separate planet and star

Spectral resolution: Instrument-dependent

Optical shape/area: Circular, 50 m^2

Nulling/blocking: Cat's-eye nuller

SNR and Msmt limit: 5 in 3 hrs (@ R=3)

Rejection of backgrounds: Confusion 0.01 obj./as^2; imaging: exozodi-insensitive

Temporal resolution: N/A

Orbit: Not critical

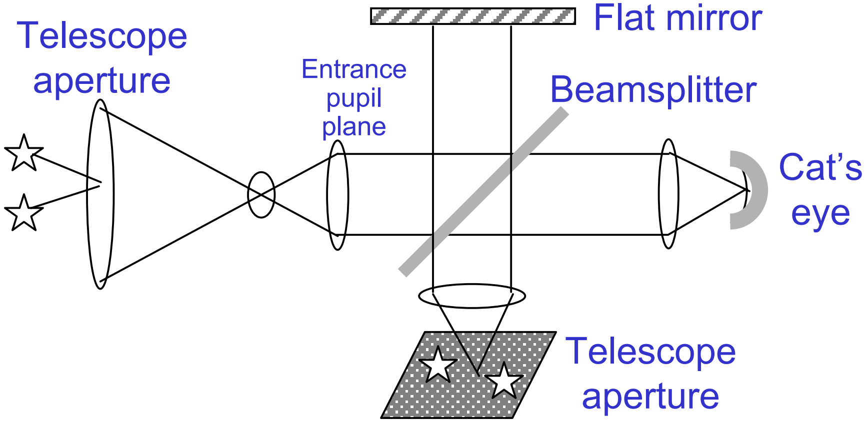
Sky coverage: Solar exclusion >60 deg

Mission thruput/timelines: One det in 6 hr

Robustness: Favors small star diameter and large planet/star separation

Astrophysics: Image doubling makes image interpretation more difficult. Should switch to another instrument if possible.

Future Missions: Image doubling complicates use for future planet imager



Candidate #4 – Focal Plane Phase Mask *(Possible)*

Description: Telescope with cross-phase focal plane coronagraph: quadrants with alternating ± 90 deg phase offsets; star image centered on the cross

Weakness: Accuracy and chromaticity of the 90 deg phase offsets; tight pointing

Wavelength: 0.3 - 1.0 µm

Spectral resolution: 20 - 200

Optical shape/area: Circular

Nulling/blocking: Yes

SNR and Msmt limit: TBD

Rejection of backgrounds: Confusion 0.01 obj./as^2; imaging: exozodi-insensitive

Temporal Resolution: N/A

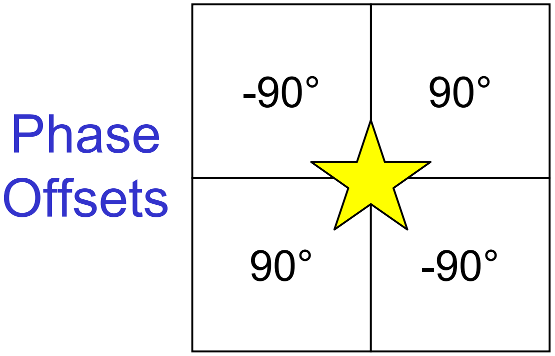
Orbit: Not critical

Sky Coverage: All

Mission thruput/timelines: Rotation for speckle

Robustness: Favors small star diameter and large planet/star separation

Astrophysics: Telescope with other instruments could do HST-follow-on science



Possibility – “Filter-Wheel” Coronagraph

Description: Instrument combines several coronagraph pupils and masks so that a choice can be made of the most suitable one for a given observational circumstance

Virtue: Adaptable for optimum planet finding, planet characterization, and astrophysics

Wavelength: 0.3 - 2.3 μm

Spectral resolution: Instrument-dependent

Optical shape/area: Circular , 50 m^2

Nulling/blocking: Yes

SNR and Msmt limit: 5 in 3 hrs (@ R=3)

Rejection of backgrounds: Confusion 0.01 obj./as^2; Imaging: exozodi-insensitive

Temporal Resolution: N/A

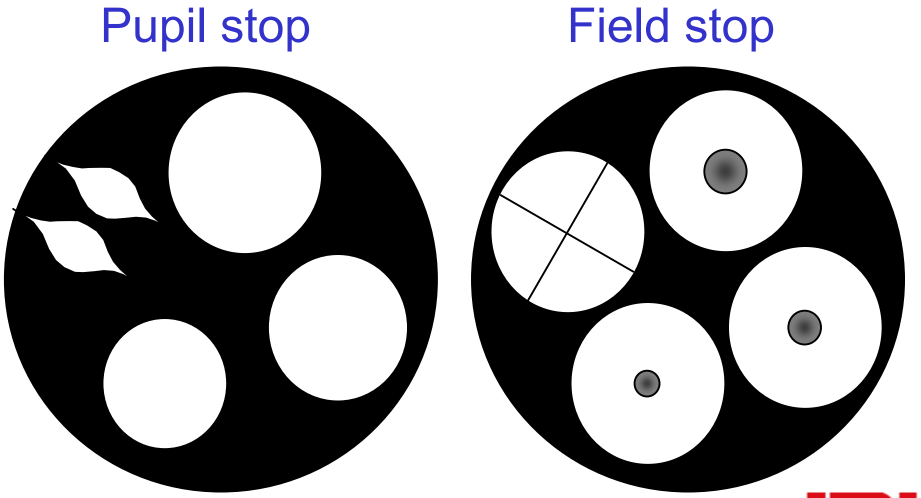
Orbit: Not critical

Sky Coverage: All

Mission thruput/timelines: Snapshot of target sufficient to detect planet

Robustness: Favors small star diameter and large planet/star separation

Astrophysics: Variety of stops and masks tailors performance to object measured



Possibility – Coronagraph and Outriggers *(Possible)*

Description: Optical space interferometer of 36 telescopes, each 0.2 m diameter, on free-flying spacecraft set on a 100 m baseline. Large telescope at center unit can act as combiner or as stand-alone coronagraph.

Weaknesses: Only get a 10 x 10 pixel image, over a FOV of 0.5 arcsec. Requiring multiple images for planet hunting.

Wavelength: 0.5 - 2 μm

Spectral resolution: 100 (but 3 for finding and 20 for characterization)

Optical shape/area: 36 apertures, 0.2 m diameter

Nulling/blocking: Any coronagraph type

SNR and Msmt limit: TBD

Rejection of background: Confusion 0.01 obj./as^2; imaging: exozodi-insensitive

Temporal resolution: Seconds

Orbit: Earth-Sun L2

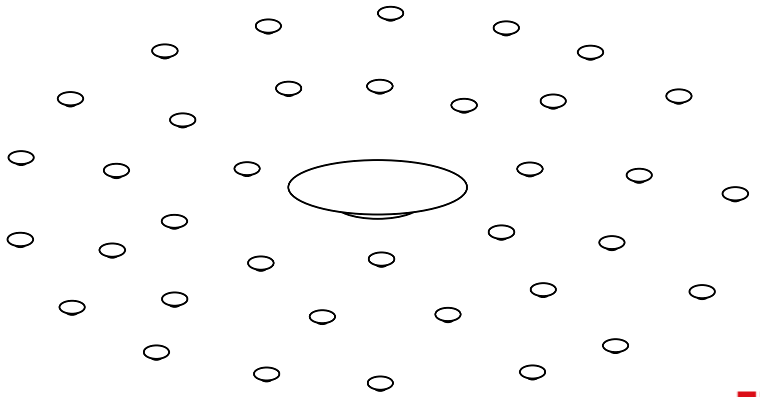
Sky Coverage: Ecliptic latitude < 45 deg, anti-Sun offset < 45 deg

Mission thruput/timelines: Observations vary from seconds to months

Robustness: Wide variety of operating modes possible, covers many situations

Astrophysics: Angular resolution of 2 mas plus fairly good PSF permits excellent high-res. imagery

Future: May demonstrate key dilute-aperture technology (Planet Imager)



Candidate #5 – Microtube Block *(Rejected)*

Description: A great many extremely narrow parallel tubes, a microchannel block gives narrow FOV across wide aperture; aiming at the planet can baffle out the star's light.

Weaknesses: Impractical aspect ratio (10 μm if 20 m long) and alignment requirement; does not suppress off-axis starlight.

Wavelength: Short, to keep tube length small

Spectral resolution:

Optical shape/area:

Nulling/blocking

SNR and Msmt limit:

Rejection of backgrounds:

Temporal resolution:

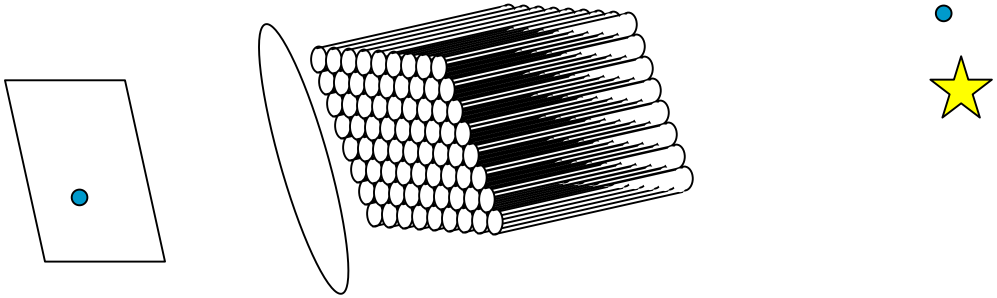
Orbit:

Sky coverage:

Mission thruput/timelines:

Robustness:

Astrophysics:



Candidate #6 – Occulting Screens *(Rejected)*

Description: Distant artificial or natural object, 100,000 km away, blocks starlight from telescope.

Virtues: Very simple optics, spectrum accuracy insensitive to nulling performance.

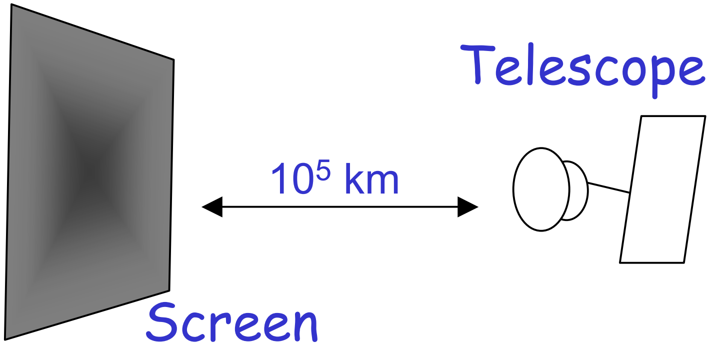
Weakness: Pointing to many objects is time consuming. Poor spatial resolution leads to contamination of spectra. May only work for stars within 3 pc.

Wavelength: 0.4 - 2.5 μm
Spectral resolution: 20 - 100
Optical shape/area: 5 m
Nulling/blocking: 70 m x 70 m screen with apodized edges
SNR and Msmt limit: Depends on telescope
Rejection of backgrounds: Conf. 0.01 obj./as^2

Temporal resolution: hours
Orbit: Earth-trailing, L2, Jupiter gravity-assist
Sky coverage: 45 deg < Sun angle < 90 deg
Mission thruput/timelines: 0.05 - 0.5 planetary systems/day
Robustness: Variable separation covers angular separation; undemanding optics

Astrophysics: Occulter difficult to position. Tiny FOV (~1 resolution element per integration time)

Future Missions: Could play some role in a huge instrumentation array



Candidate #7 – Spergel Pinhole Screen *(Rejected)*

Description: Spergel "eye" shape as an occulting mask or diffracting aperture; telescope ~8 m diam, hundreds of km away, collects planet light.

Virtues: Simple mask, low-technology telescope

Weaknesses: Maneuvering and repointing

Wavelength: Short, to keep size down

Spectral resolution: 50 - 200

Optical shape/area: 50 m^2

Nulling/blocking: Spergel occulter

SNR and Msmt limit: TBD

Rejection of background:

Temporal resolution: Hours

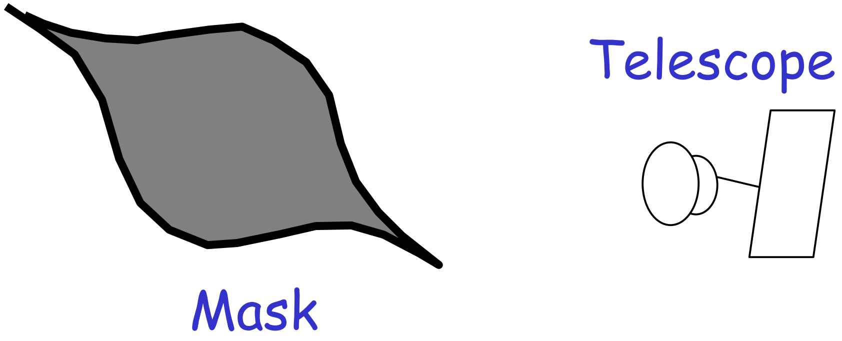
Orbit: L2, Earth trailing, Princeton

Sky coverage: 45 deg < solar exclusion <90 deg

Mission thruput/timelines: 1 per 10 days

Robustness: Only the formation flying is hard

Astrophysics: For any observation near a very bright noise source.



Emitted-Light (MIR) Candidates

No.	Candidate	Captain(s)
8	Interferometer Full-Monolith	Kasdin/Hyde
9	Interferometer Lite-Monolith	Noecker
10	Interferometer 2D Tethered	Kasdin
11	Interferometer Linear Tethered	Kasdin
12	**Interferometer Free-Flyer – Chopping Linear DAC**	Noecker
13	Interferometer Free-Flyer Chopping Dual Bracewell	Noecker
14	**Interferometer Free-Flyer – Laurance**	Penny
15	Interferometer Free-Flyer – Mariotti Triangle	Noecker
16	Interferometer Free-Flyer – TPF-Lite	Noecker
17	Interferometer Free Flyer Fizeau	Noecker
18	Interferometer Free Flyer Hypertelescope	Noecker
19	Interferometer Free Flyer Mini-hypertelescope	Noecker
20	Super-shielded Interferometer Array	Kilston
21	**Interferometer Cable-Car Linear DAC**	Kilston

Performance Characteristics of Emitted-Light Candidates

#1 Planet Finding and Characterization	
Virtues for Planet Finding:	Total Planet/Star contrast best in IR Adjustable baseline easily selects most appropriate angular resolution
Virtues for Planet Characterization:	Strong biomarker spectral features available at modest resolution Penetrates dust for protoplanetary disk studies in inclined systems
Weaknesses:	Entire exo-zodi cloud contributes to background noise, lowering SNR Angular scale varies with wavelength
#2 Astrophysics	
Virtues:	Variable-baseline synthesis imaging at very high angular resolution, Nulling imaging at sub-arcsecond angular resolution High MIR sensitivity, views and penetrates dust
Weaknesses:	Time and fuel vs. source complexity and dynamic range Wavelength coverage similar to NGST
#7 Future Missions Planet imaging uses nulling interferometers to isolate planet light for synthesis imaging	
Virtues:	Clean wavefronts of planet light, for stable fringe visibility
Weaknesses:	Each wavelength must be imaged separately High background – Very small fringe visibilities

Common Characteristics of Emitted-Light Architectures (1)

- Collection of small apertures combined interferometrically
  - Nulling: Collimated beam combination with precise subtraction to suppress stellar optical field
- Baseline sets angular resolution
  - Adjustable to match each planet system.
- Angle proportional to wavelength
  - Interferometric “bright spots” pass across planet at different times for each wavelength
  - Full wavelength scan on a planet requires array rotation and/or resizing
  - Complicates its use for Planet Imager
- PSF of individual telescopes typically covers entire exo-planet system
  - Limits outer radius of detectability
  - Impacts on SNR (next page)

Common Characteristics of Emitted-Light Architectures (2)

- Signal to noise vs. aperture diameter
  - Principal backgrounds are local zodi and exo-zodi
    - Photons/sec largely independent of aperture diameter
    - Shot noise in this background is limiting noise source
  - Planet signal proportional to aperture collecting area (D^2)
  - Signal to noise proportional to D^2 – integration time declines as D^4
  - This is largely independent of baseline, until stellar leakage begins to dominate
- Planetary system imaging
  - Synthesis imaging using a collection of “apertures” each of which is a nulling interferometer that isolates planet light
  - Large background signal (zodi) leads to TINY fringe visibility
  - Interferometric stripe lands on planet for only one wavelength at a time
    - Synthesis imaging must be done one wavelength at a time modest-sized passband

Reasons for Some of Our Interferometer Assumptions

- Formation-flying is superior to monoliths in important ways
  - Permits planet detection at a wider range of angles (by adjusting baseline)
  - Resolves background confusion ambiguities (by adjusting baseline)
  - Enables a wider variety of astrophysics (by extending baseline farther)
  - More credible testing on the ground if there's no long structure – especially in MIR (cold) systems
- However, free-flyers also have negatives
  - Contamination, power, mass
- Chopping or imaging systems only
  - Non-chopping, non-imaging means single-pixel, quasi-static detection
    - Many technical errors could mimic planet signal
  - Chopping shifts the signal to a frequency above that of the technical errors
  - Imaging allows comparison with adjacent pixels through a rotation around the line of sight

Chopping Nullers Have a Serious Systematic Bias Problem

- Problem applies to all interferometers which use
  - Two linear nulling interferometers, interleaved and offset by some fraction of the aperture spacing
  - Combination of the starlight-suppressed (“dark”) beams with alternating ± 90 deg phase chopping
- Modulation amplitude is unimportant, but modulation symmetry is <u>crucial</u>
  - Phase chopping between +100 deg and -100 deg scales the sensitivity to an existing planetary signal (decreases it)
  - Phase chopping between +89 deg and -91 deg produces a false planet signal
- Possible solutions
  - Phase closure (three nulling interferometers and 3 modulating signals)
  - Divert some starlight to control the cophasing (i.e., chopping symmetry)

Candidate #8 – Interferometer – Full Monolith *(Possible)*

Description/Approach: Linear interferometer with 4-6 apertures mounted on a structure up to 100 m long, apertures each at least 3 m in diameter.

Virtues: Thermal and light shielding over entire instrument; rotation via reaction wheels.

Weaknesses: Vibration, limited baseline (< 100 m), launch and deployment.

Wavelength: 7 - 24 μm

Spectral resolution: 3 - 20

Nulling/blocking: Chopped Dual-DAC.

SNR & Msmt. limit:

Rejection of background: Poor

Temporal resolution: Hours

Orbits: Preferred out of ecliptic plane

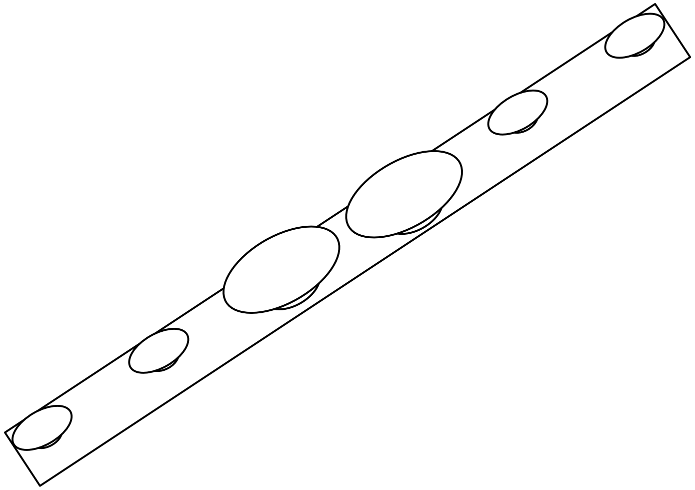
Sky coverage: >90 deg from Sun

Mission thruput/timeline: Up to 2 stars/day

Robustness: Not much adjustability

Astrophysics: Very limited u-v-plane coverage if fixed telescopes. 5 - 10 mas resolution.

Future Missions: Suitable as a means of extracting planet light before synthesis imaging of planet.



Candidate #9 – Interferometer Lite Monolith *(Rejected)*

Description/Approach: Linear interferometer with 4 apertures mounted on a structure 30 to 100 m long, apertures each at least 1 - 1.5 m in diameter.

Virtues: Thermal and light shielding over entire instrument; rotation via reaction wheels.

Weaknesses: Vibration, limited baseline, deployment mechanisms.

Wavelength: 7 - 24 μm

Spectral resolution: 3 - 20

Nulling/blocking: Chopped Dual-Brace.

SNR & Msmt. limit:

Rejection of background: Poor

Temporal resolution: Hours

Orbits: 5 AU

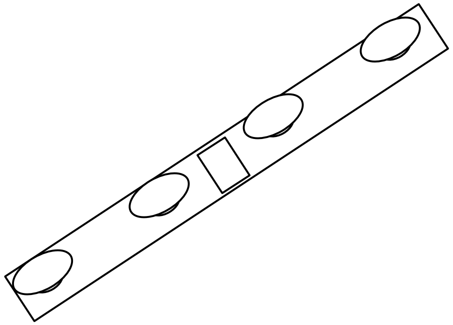
Sky coverage: Within 70 degrees of ecliptic

Mission thruput/timeline: 1-3 star/day

Robustness: Not much adjustability

Astrophysics: Very limited u-v-plane coverage if fixed telescopes; 10 - 20 mas resolution.

Future Missions: Suitable as a means of extracting planet light before synthesis imaging of planet.



Candidate #10 – 2D Interferometer Tethered *(Rejected)*

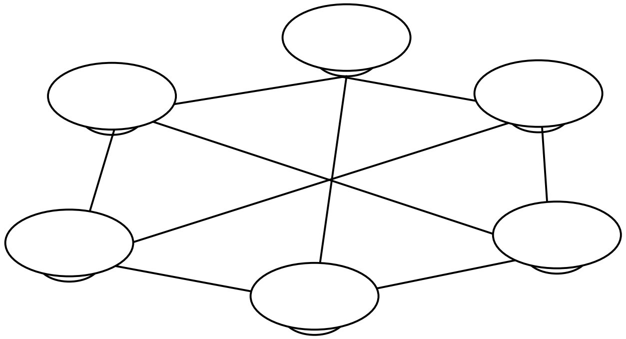
Description: Semi-free-flyers, anchored by cables.
Virtue: Common power and communications, needs much less propellant than free-flyers.
Weaknesses: Dynamics of tether, difficult to shield stray light from the tether. (It sits in sunlight, and has to stretch between spacecraft, right next to where the starlight goes.)

Wavelength:
Spectral resolution:
Nulling/blocking:
SNR and Msmt limit:
Rejection of background:

Temporal resolution:
Orbits:
Sky coverage:
Mission thruput/timeline:
Robustness:

Astrophysics:

Future Missions:



Candidate #11 – Linear Tethered Interferometer *(Rejected)*

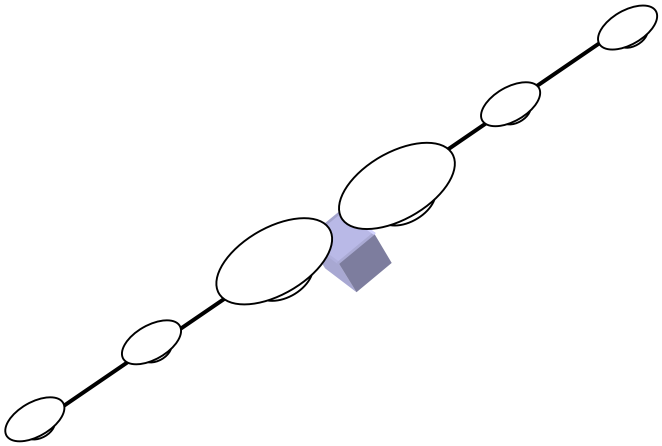
Description: Semi-free-flyers, anchored by cables.
Virtue: Can reduce mass by using common subsystems, as in monolith; e.g., might use one common solar array.
Weaknesses: Dynamics of tether, difficult to shield stray light from the tether. (It sits in sunlight, and has to stretch between spacecraft, right next to where the starlight goes.)

Wavelength:
Spectral resolution:
Nulling/blocking:
SNR and Msmt limit:
Rejection of background:

Temporal resolution:
Orbits:
Sky coverage:
Mission thruput/timeline:
Robustness:

Astrophysics:

Future Missions:



Candidate #12 – Free-Flyer Chopping Linear DAC *(***Top 5***)*

Description/Approach: Six telescopes + combiner, free flyers, individual sunshields on each spacecraft; dual-DAC-chopped nulling strategy.

Wavelength: 7 - 20 µm

Spectral resolution: 20

Optics/area: 4 x 3.5m diam

Nulling/blocking: Achromatic null beam

SNR and Msmt. limit: 5 in 9 hrs (@ R=3)

Rejection of background: Planet/exo-zodi = 1/100, planet/local-zodi= 1/200, confus. 2-200 obj/as^2

Temporal resolution: ~hours (single λ passband)

Orbits: L2, Earth-trailing, Jupiter, Princeton

Sky coverage: |Ecliptic Latitude| <45 deg

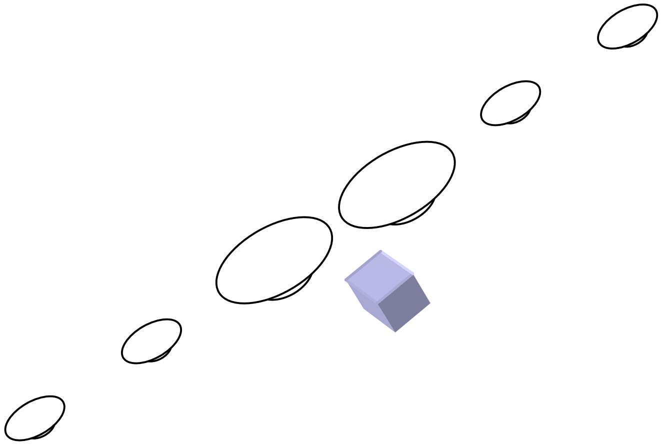
Mission thruput/timeline: One detection in 6 hours

Robustness: Variable baselines allow for distant stars, vulnerable to exo-zodi

Astrophysics: Virtues: Variable-baseline synthesis imaging.

Weaknesses: Formation re-position time, u-v-plane coverage.

Future Missions: Applicable for isolating planet light for synthesis imaging.



Candidate #13 – FF Chopping Dual Bracewell Interferometer *(Rejected)*

Description/Approach: 4 telescopes + combiner on 5 spacecraft, free flyers, chopping dual Bracewell

Virtue: Simple beam combination.

Weaknesses: Large starlight leakage

Wavelength: 7 - 20 μm

Spectral resolution: 3-20

Optics/area: (4 x 3.5m diam)

Nulling/blocking: Achromatic null

SNR and Msmt. limit:

Rejection of background: Planet/exo-zodi= 1/100, planet/loc-zodi=1/200, confus. 2-200 obj/as^2

Temporal resolution: ~hours (single l passband)

Orbits: L2, Earth trailing, Jupiter, Princeton

Sky coverage: >135 deg from Sun

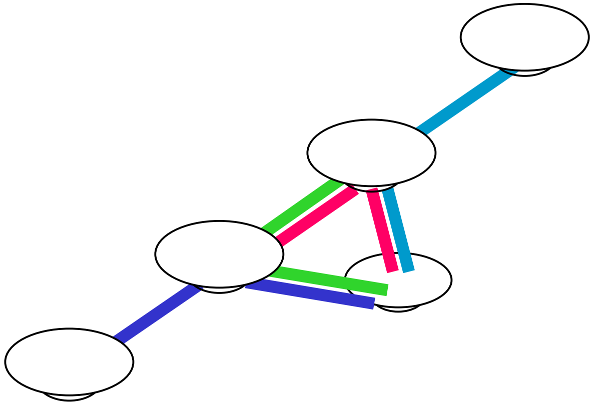
Mission thruput/timeline: TBD

Robustness: Variable baselines allow for distant stars, vulnerable to exo-zodi

Astrophysics:

Virtues: Variable baseline synthesis imaging. *Weakness:* Formation reposition time, u-v-plane coverage.

Future Missions: large background



Candidate #14 –Laurance ("Super-Darwin") Interferometer *(***Top 5***)*

Description/Approach: Mid-IR space interferometer, six cold telescopes on free flyers in circle around combiner, Laurance-chopped nulling. ("Super-Darwin" if aperture ≥ 3 m)

Virtues: Only 60 deg rotation needed; potentially resolves chopping-symmetry bias.

Weaknesses: More spacecraft to fly, more complex beam combination and chopping, interferometric pattern doesn't hit all planet angles on first try.

Wavelength: 4 - 23 μm

Spectral resolution: 100, but 1 for planet finding, 20 for planet char

Optics shape and area: 6 x (1.5 - 3.5m) circ.

Nulling/blocking: Achromatic null $>10^{6}$

SNR and Msmt. Limit: SNR = 5 in 20 hrs (R=3; Earth @ 10pc)

Rejection of background: Planet/exo-zodi = 1/100, planet/local-zodi= 1/200, confus. 2-200 obj/as^2

Astrophysics: Same as the others, but possibly faster for imaging

Future Missions: Same as the others

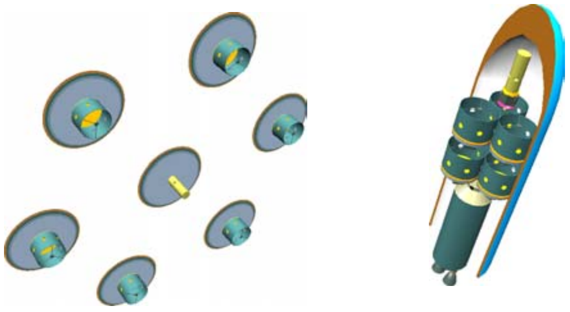
Temporal resolution: Minutes

Orbit: Earth-Sun L2

Sky coverage: Ecliptic latitude <45 deg; at any one time, anti-Sun offset <45 deg

Mission thruput/timelines: Observations vary from 2 hrs to 3 months

Robustness: B/L tunable to star distance/star-planet sep.; vulnerable to large or structured exozodi; can lose 1 collector yet function



Candidate #15 – Darwin Mariotti Interferometer *(Possible)*

Description/Approach: Mid-IR space interferometer, six cold telescopes on free flyers in triangles in single plane around combiner, Mariotti-chopped nulling.

Virtues: Only 60 deg rotation needed, potentially resolves chopping symmetry bias.

Weaknesses: more spacecraft to fly, more complex beam combination and chopping, interferometric pattern doesn't hit all planet angles on first try.

Wavelength: 7 - 20 µm

Spectral resolution: 3-20

Optics shape and area: 6 x (1.5 - 3.5m) circular

Nulling/blocking: Achromatic null

SNR and Msmt limit:

Rejection of background: Planet/exo-zodi = 1/100, planet/local-zodi= 1/200, confus. 2-200 obj/as^2

Temporal resolution: Minutes

Orbit: L2, SIRTF, Princeton

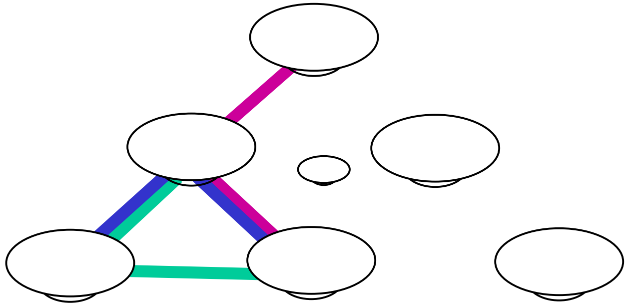
Sky coverage: >135 deg from Sun

Mission thruput/timelines: Observations vary from 2 hrs to 3 months

Robustness: B/L tunable to star distance/star-planet sep.; vulnerable to large or structured exozodi

Astrophysics: Same as the others

Future Missions: Same as the others



Candidate #16 – TPF-Lite FF Interferometer *(Rejected)*

Description: Four 1-meter class telescopes plus combiner, free-flying; telescopes not as cold, dual Bracewell chopped.

Virtues: Easier to implement.

Weaknesses: Degraded sensitivity; larger minimum angle; habitable zones of fewer stars.

Wavelength: 4 - 11 μm

Spectral resolution: 3, (20 for warm Jupiter)

Optical shape/area: 4 x (0.8 - 1.0m)

Nulling/blocking: achromatic null >10^6

SNR and Msmt limit: 5 in 400 hrs (R=3; Earth @10pc)

Rejection of background: Planet/Exo = 1/100, Planet/Local = 1/200; Conf 2-200 obj/as^2

Temporal resolution: Minutes

Orbit: Earth-Sun L2. SIRTF, Princeton

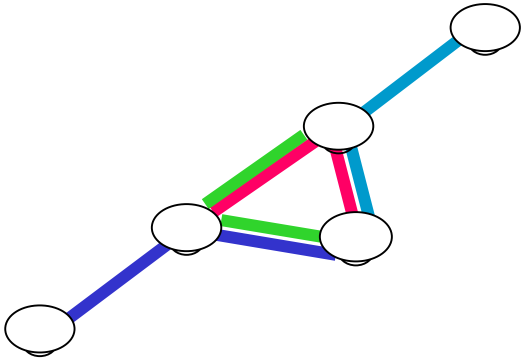
Sky coverage: Ecliptic latitude < 45 deg, at any one time, anti Sun offset <45 deg

Mission thruput/timelines: Observations vary from 2 hours to 3 months

Robustness: Baseline tunable to star distance/ star-planet sep.; vulnerable to large or structured exozodi

Astrophysics: Simple synthesis imaging and nulling imaging

Future Missions: Only for the brightest, largest-angle planets



Candidate #17 – Fizeau Interferometer *(Supplementary)*

Description: Formation flying sparse-aperture telescope obeying the "Golden Rule" for large FOV

Virtue: Enhanced angular resolution

Weaknesses: Multiple ghost images; stellar leakage

Wavelength: Any

Spectral resolution: 20 - 200

Optical shape/area: ≥10 apertures, 1 - 1.5m diameter

Nulling/blocking: Not suitable

SNR and Msmt limit: Not calculated

Rejection of backgrounds: Poor

Temporal resolution: ??

Orbit: L2, SIRTF, Princeton

Sky Coverage: >120 deg from Sun

Mission thruput/timelines: Unknown

Robustness: Medium, with effort

Astrophysics: Virtues: Enhanced angular resolution, wide FOV

Weaknesses: Sparse MTF – multiple ghosts, ambiguity in results

Future Missions: May be hard to isolate planet light for synthesis imaging

Candidate #18 – Hyper-Telescope *(Rejected)*

Description: Formation flying sparse-aperture telescope violating the "Golden Rule" for the sake of improved PSF in small FOV.

Virtues: Enhanced angular resolution.

Weaknesses: Large number of telescopes; degraded PSF off-axis; tiny FOV.

Wavelength: Any

Spectral resolution: 20 - 200

Optical shape/area: ≥100 apertures, 0.1 - 1 m

Nulling/blocking: Nulling coronagraph

SNR and Msmt limit: Not calculated

Rejection of background: Poor

Temporal resolution: TBD

Orbit: L2, SIRTF, Princeton

Sky coverage: >120 from Sun

Mission thruput/timelines: Unknown

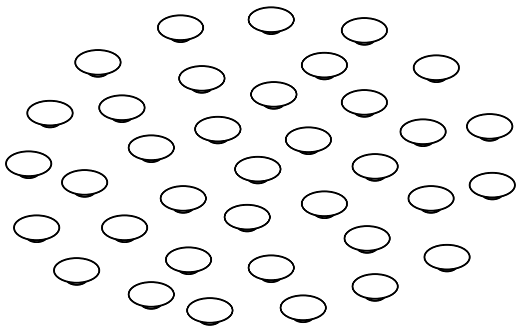
Robustness: Poor due to bad PSF

Astrophysics:

Virtues: Enhanced angular resolution

Weaknesses: tiny FOV; sparse MTF – ambiguity in results, confusion in backgrounds

Future instruments: Bad off-axis PSF complicates its use in synthesis imaging system.



Candidate #19 – Guyon-Roddier Mini-Hyper-Telescope *(Rejected)*

Description: Free flyer sparse-aperture telescope violating the “Golden Rule” for the sake of improved PSF in a small FOV

Virtues: Enhanced angular resolution.

Weaknesses: Multiple-object confusion; tiny FOV.

Wavelength: 7-20 um

Spectral resolution: 20 - 200

Optical shape/area: 6 apertures, 1 - 1.5 m

Nulling/blocking: Field mask or nuller

SNR and Msmt limit: Not calculated

Rejection of background: Poor

Temporal resolution: TBD

Orbit: L2, SIRTF, Princeton

Sky coverage: >120 from Sun

Mission thruput/timelines: Unknown

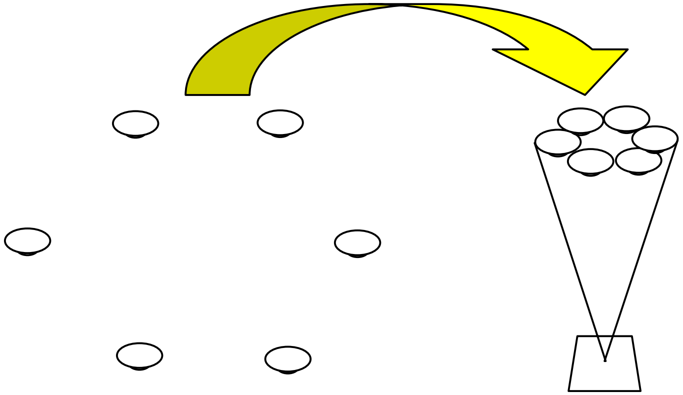
Robustness: Poor

Astrophysics:

Virtues: Enhanced angular resolution

Weaknesses: tiny FOV; sparse MTF – ambiguity in results, confusion in backgrounds

Future instruments: Bad off-axis PSF complicates its use in synthesis imaging system.



Candidate #20 – Super-shielded FF Interferometer Array *(Rejected)*

Description: Any of the preceding free-flyer interferometers with one common large sunshield (0.1-1 km in diameter) shading all telescopes and combiner

Virtues: Expanded sky coverage, unlimited rotations, more effective passive cooling

Weaknesses: Station-keeping propulsion and power, ground testability

Wavelength: 7 - 20 μm

Spectral resolution: 3-20

Optical shape/area: 6 x 2-4 m diam.

Nulling/blocking: Achromatic null

SNR and Msmt limit:

Rejection of background:

Temporal resolution: Hours

Orbit: L2. Earth trailing. Jupiter, Princeton

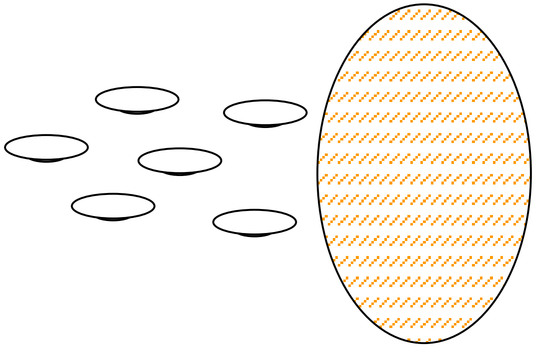
Sky coverage: > 60 deg from Sun

Mission thruput/timelines: ??

Robustness:

Astrophysics: *Virtues:* large sky coverage. *Weaknesses:* Possible super shield size limitation, station-keeping propulsion.

Future Missions: Same as the others.



Candidate #21 – Cable-Car Interferometer *(***Top 5***)*

Description: Mid-IR interferometer; four telescopes + combiner, compromise between structure (for re-positioning) and free flyers (for data collection), single sunshield or individual sunshields on each spacecraft; dual Bracewell-chopped nulling structure strategy.

Virtues: Electrical baseline adjustment, reduced propellant and contamination.

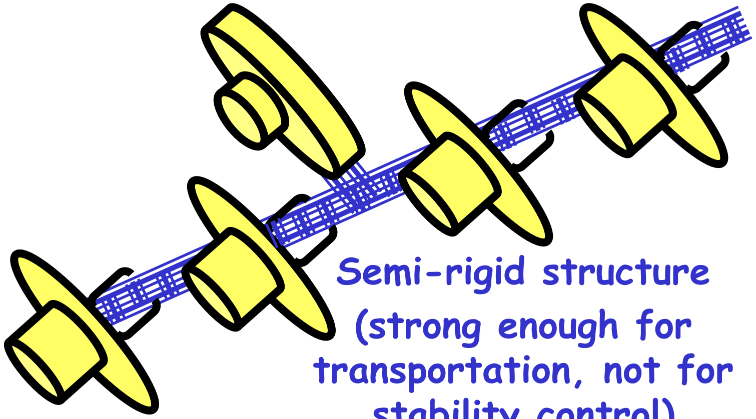
Weaknesses: Limited baseline, exozodi confusion, much new technology.

Wavelength: 7-20 μm
Spectral resolution: 20
Optical shape/area: 4 x 3.5m diam.
Nulling/blocking: Nulling > 10^6
SNR and Msmt limit: SNR=5 in 2hr. (at R=3)
Rejection of background: Planet/exo-zodi = 1/100, planet/local-zodi= 1/200, confus. 2-200 obj/as^2

Temporal resolution: Hours (single l passband)
Orbit: L2' Earth-trailing, Jupiter, Princeton
Sky coverage: |Ecliptic latitude| <45 deg
Mission thruput/timelines: One det. in 6 hr.
Robustness: Variable baselines allow for more stars. Vulnerable to large exozodi

Astrophysics: *Virtue:* Variable B/L synthesis imaging with good u-v plane coverage, nulling imaging

Future Missions: Might be the best technology for lengthy missions.



Semi-rigid structure (strong enough for transportation, not for stability control)

Diversity Candidates

We include and describe these architectures which cannot do the entire TPF mission, because information they provide will help focus the actual TPF architecture on what the true exoplanets are.

No.	Candidate	Captain(s)
22	Gravitational microlensing	Seager/Turner
23	Transit photometry	Tim Brown
24	Transit spectroscopy	Tim Brown
25	Other secular variations	Seager
26	Planet effects on exo-zodi	Telesco
27	Stellar astrometry	R. Brown
28	Stellar Doppler shifts	Seager
29	Large ground-based Telescope	Penny

Candidate #22 – Gravitational Microlensing *(Supplementary)*

Description/Approach: Detect planets by gravitational microlensing. The planet/star system is not visible but acts as a lens when it passes in front of a distant star and gravitationally focuses the light.
Virtues: Can provide frequency and parameters of planetary systems in our Galaxy.
Weaknesses: Planet mass and orbital period constrained to within a factor of a few. Planets too distant for follow-up.

Wavelength: Visible

Spectral resolution: Not needed. Colors useful.

Optical shape/area: Various

Nulling/blocking: Not required

SNR and Msmt limit: Depends

Rejection of background: N/A

Temporal resolution: 20 minutes

Orbit: Not critical

Sky coverage: Need to observe dense fields

Mission thruput/timelines: Years

Robustness: Sensitive to planet/star mass ratios.

Astrophysics: *Virtues:* Galactic structure, Binary star frequency, Variable stars**.**

Weaknesses: No spectroscopy, no imaging, limited to brightness changes.

Candidate #23 – Transit Photometry *(Supplementary)*

Description/Approach: Identify Earth-sized transiting habitable-zone planets out to 1000 pc, using staring system doing precise time-series photometry on Galactic arm.

Virtues: Makes directed survey to some size limit within 3 orbits around A to M stars. Measure orbital periods and sizes of planets, albedos, frequency near binary stars.

Weakness: Applicable only to the small fraction of planets showing transits of 5 - 25 hrs.

Wavelength: Vis./near IR

Spectral resolution: N/A

Optical shape/area: 15 cm to 1 m aperture

Nulling/blocking: Not required

SNR and Msmt limit: Limited by photon noise

Rejection of background: Possible confusion form faint background eclipsing binaries.

Temporal resolution: 15 min

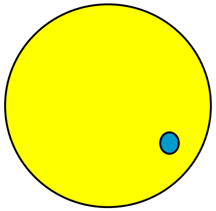
Orbit: Not near Earth

Sky coverage: All

Mission thruput/timelines: 1 transit/day, 3 orbital times to confirm orbit.

Robustness: Less sensitive with smaller radius planets, larger radius stars.

Astrophysics: Provides time-resolved photometry of all nearby stars, valuable for studies of stellar structure (p modes) and magnetic activity, but wavelength discrimination is poor to none.



Candidate #24 – Transit Spectroscopy *(Supplementary)*

Description/Approach: Characterize atmospheres of known transiting planets using very high SNR spectroscopic measurements taken in and out of planet transit, and during occultation of planet by star.

Virtues: Able to measure composition of atmospheres of known transiting planets.

Weakness: Planet atmosphere must have strong spectral features.

Wavelength: 0.3 - 2.3 μm

Spectral resolution: > 1000 (instrumental) but degraded to ~20 for analysis purposes

Optical shape/area: 20 m filled-aperture

Nulling/blocking: N/A

SNR and Msmt limit: Limited by photon noise

Rejection of background: Correction for limb darkening of stellar spectra required.

Temporal resolution: Hours

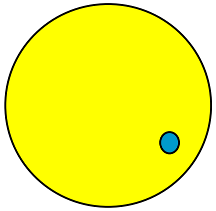
Orbit: Not near Earth (for high SNR)

Sky coverage: All

Mission thruput/timelines: Roughly 1 planet per day, revisit per planet's orbital period

Robustness: Less sensitive with smaller radius planets, larger radius stars

Astrophysics: Provides time-resolved spectroscopy of reasonably isolated astrophysical sources.



Candidate #25 – Other Secular Variations *(Supplementary)*

Description/Approach: Characterize Earth-like planets from secular variations (daily and yearly variations) of flux.

Virtues: Potentially detect weather and oceans, and characterize atmospheric chemicals for known targets. Models of surface composition components, clouds, snow, etc., show up to factor of 2 variations in their visible-band light curves.

Weakness: Need high dynamic range.

Wavelength: Visible

Spectral resolution: Not needed

Optical shape/area: Various

Nulling/blocking: Required

SNR and Msmt limit: ?

Rejection of background: N/A

Temporal resolution: Days

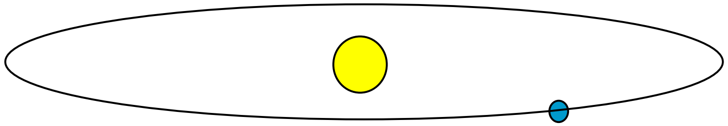
Orbit: Per targets

Sky coverage: N/A

Mission thruput/timelines: N/A

Robustness: Planets with smaller orbital distances or larger surface areas have more reflected light.

Astrophysics: Same as reflected light architectures.



Candidate #26 – Planet Effects on Exo-Zodi *(Supplementary)*

Description/Approach: For planets orbiting newly formed stars, the gap a planet opens in an accretion disk can be viewed. This might give information on a planet's mass, and similar effects (such as Lagrangian point debris concentrations, or debris trails) conceivably might give us some information on the planet.

Wavelength: Visible through MIR

Spectral resolution:

Optical shape/area: Large enough for good spatial resolution

Nulling/blocking

SNR and Msmt limit:

Rejection of background:

Temporal resolution:

Orbit:

Sky coverage:

Mission thruput/timelines:

Robustness:

Astrophysics:

Candidate #27 – Stellar Astrometry *(Supplementary)*

Description: Use high-accuracy stellar astrometry to detect the elliptical reflex motion of the stellar photocenter and thereby infer properties of the orbiting planet.

Virtues: Planet cannot hide, so search is exhaustive. Measures true orbit, planet mass.

Weaknesses: Finds “Earth” masses only for nearest stars. Duration must equal period.

Wavelength: Any in principle; visible in practice

Spectral resolution: Instrumentally dependent; not key factor

Optical shape/area: Various, area accuracy needs

Nulling/blocking: Not required

SNR and Msmt limit: Very high; limiting factor is noise in stellar photocenter

Rejection of background: Not required.

Temporal resolution: Optimized to sample orbits

Orbit: Not critical

Sky coverage: All

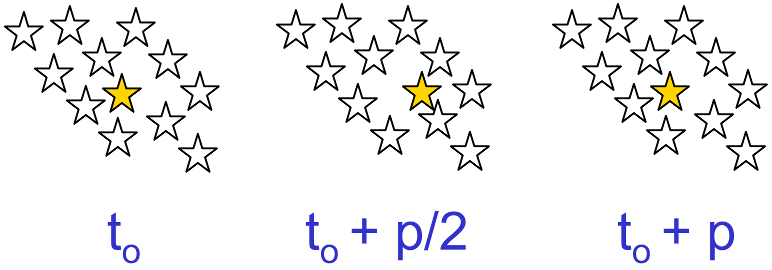
Mission thruput/timelines: Maximum semi-major axis detectable sets mission duration

Robustness: Less sensitive with lower planet/star mass ratios, increased ranges

Astrophysics: Astrometry has greater value if also wide-angle (not needed for planets); serendipitous brown dwarfs

Future: No planet atmosphere measurements, no high-resolution imaging

Feasibility from Ground Telescopes: Adaptive optics may give useful performance



Candidate #28 – Stellar Doppler Shifts *(Supplementary)*

Description: Now-established method of finding planets indirectly by measuring the radial velocity changes in their host stars through high-accuracy spectroscopy.

Virtues: Can measure distant planets, determines masses (subject to orbit inclination).

Weaknesses: Favors massive, short-period planets; stellar spectral noise will inhibit detection of smaller planets; cannot detect planets in face-on orbits.

Wavelength: Visible

Spectral resolution: 10^8 (need 10^{10} for “Earth”)

Optical shape/area: Any large enough for SNR

Nulling/blocking: N/A

SNR and Msmt limit: Very

Rejection of background: N/A

Temporal resolution: Weeks to months

Orbit: N/A

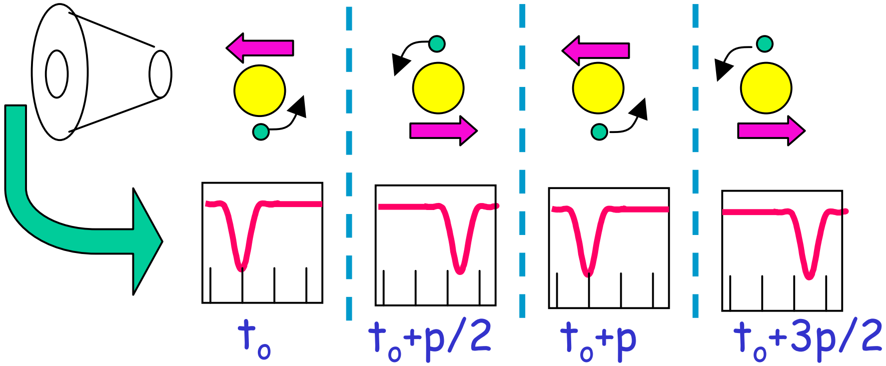
Sky coverage: All

Mission thruput/timelines: Years are needed

Robustness: Not extensible to small planets

Astrophysics: Serendipitous brown dwarfs; stellar oscillations and other atmosphere and structure information

Future: N/A



Candidate #29 – Large Ground-based Telescopes *(Supplementary)*

Description: 50 to 100m ground optical telescope, multi-conjugate adaptive optics gives diffraction limit; advanced coronagraph.
Virtues: Large collecting area; good angular resolution; flexible instrument replacement, large FOV.
Weaknesses: Sky brightness, scattered light with large star/planet brightness ratio; planet spectrum may be crowded; planet radius and temp difficult to measure

Wavelength: 0.5 - 3 μm

Spectral resolution: 1000

Optical shape/area: 50 - 100m filled aperture

Nulling/blocking: Desired is $>10^{9}$

SNR and Msmt limit: ?

Rejection of background: Very good

Temporal resolution: Minutes

Orbit: On ground

Sky coverage: 70 %

Mission thruput/timelines: Minutes to hours

Robustness: Robust against star distance and exozodi level and structure. Vulnerable to possible confused visible/NIR spectrum.

Astrophysics: Large aperture, diffraction-limited resolution, extensive and upgradeable instrumentation.

Future: Huge-optics technology development; critical for advanced space optical system.

Expected Ground-Based Telescopes – Capabilities and Limitations – J. Nelson

- Ground based optical and infrared telescopes
  - Limited ability to detect faint objects or structure near bright objects when “seeing” limited by the atmosphere
  - Only unusually bright or relatively distant objects can be detected: brown dwarfs, bright disks, etc.
- Adaptive optics (AO) and interferometry can significantly extend ground-based capabilities
  - AO should produce diffraction limited images with Strehl ratios around 80-90%
  - Perfect correction of the atmosphere at short wavelengths (< 2 µm) is impractical, so contrast ratio is limited
- At 1.6 µm, Keck AO will see objects 300,000 times fainter than a star 1 arcsec away. (Diffraction limit resolution is 0.033 mas.) Expect another factor of 10 improvement in contrast ratio
- The Keck Interferometer (KI, operational in 2003) should provide significant improvements in angular resolution and the ability to detect structures and Jovian planets in exo-solar systems
  - With an 85 m baseline, it will have angular resolution of 5 mas at 2 µm, its shortest wavelength
  - It should easily detect exo–zodiacal light 10x our solar system’s, and perhaps do significantly better
  - Expected performance of the VLTI should be as good and it will be available in the same time frame.
- To detect planets in the habitable zone the challenge for ground based observations grows rapidly
  - Angular scales are smaller, and often one wishes to observe at shorter wavelengths
  - In the near future such detections are unlikely due to large amounts of scattered light from the parent star
  - *In the next 10-20 years we expect even larger telescopes, in the 30-100m range, with AO, but it seems unlikely that Strehl ratios will improve. Backgrounds from scattered light will still be very significant, preventing these future ground based facilities from pushing their observations into the habitable zone*

F: Science Performance Analyses

Kilston, Traub, Ebbets, Seager, Spergel

- Planet Finding and Characterization Analyses
  - SNR and Integration Time
  - Atmospheric Spectra and Biomarkers
  - Star Sample Implications
  - Secular Variations
  - Confusion Impact
- Astrophysics Performance Capabilities

#1 Science Rationale – Planet Finding, Planet Characterization

The TPF SWG has provided our main science requirement in a DRP:

- "TPF must detect radiation from any Earth-like planets in the habitable zones surrounding ~150 solar type (spectral types F, G, and K) stars. TPF must: 1) characterize the orbital and physical properties of all detected planets to assess their habitability; and 2) characterize the atmospheres and search for potential biomarkers among the brightest candidates for Earth-like planets."

We begin to flowdown these requirements with the following assumptions:

- Detect — Repeatable observations with SNR of at least 5
- Earth-like Planets — Planets from one-half to twice the radius of Earth
- Habitable Zones — The loci of orbits where an Earth-sized planet would be heated by its star to temperatures permitting liquid H_2O retention at 1 atm pressure (which could involve some planet and atmosphere evolution)
- 150 FGK Stars — Nearby representatives of these stellar types satisfying the criterion of **intrinsic detectability** of any Earth-like Planets in their Habitable Zones

Performance Criteria for Planet Finding, Planet Characterization

- Implications of the Design Reference Program
  - For exoplanets, "better" science performance means:
    - More stars surveyed, more planets found, and more planets characterized
    - Planets better characterized
    - More information gathered that is helpful with interpretations
  - Therefore we have found a **"key tradeoff"** between:

    (1) Necessary integration time and

    (2) Inner working distance (IWD)
  - Biomarkers which we think measure habitability include:
    - Atmospheric chemical constituents
    - Planet temperature (from IR continuum, orbital radius, star luminosity)
    - Secular variations indicating rotation period or actual seasonal changes
  - A broader framework that includes the properties of all planetary system constituents, e.g. both gas giant and terrestrial planets, and debris disks.

    → Ability to search the region from ~ 0.5 AU out to ~ 20 AU and detect any major planets present is a strong advantage of any design

Main “Intrinsic Detectability” Factors

SIGNAL FACTORS

- Brightness of planet
  - Spectral passband observed
  - Brightness of star (for IR, total intrinsic luminosity; for visible, brightness in passband)
  - Orbit radius
  - Planet size
  - Planet phase, albedo
  - Distance from us

TIME FACTORS (WHEN IS PLANET MOST EASILY VISIBLE)

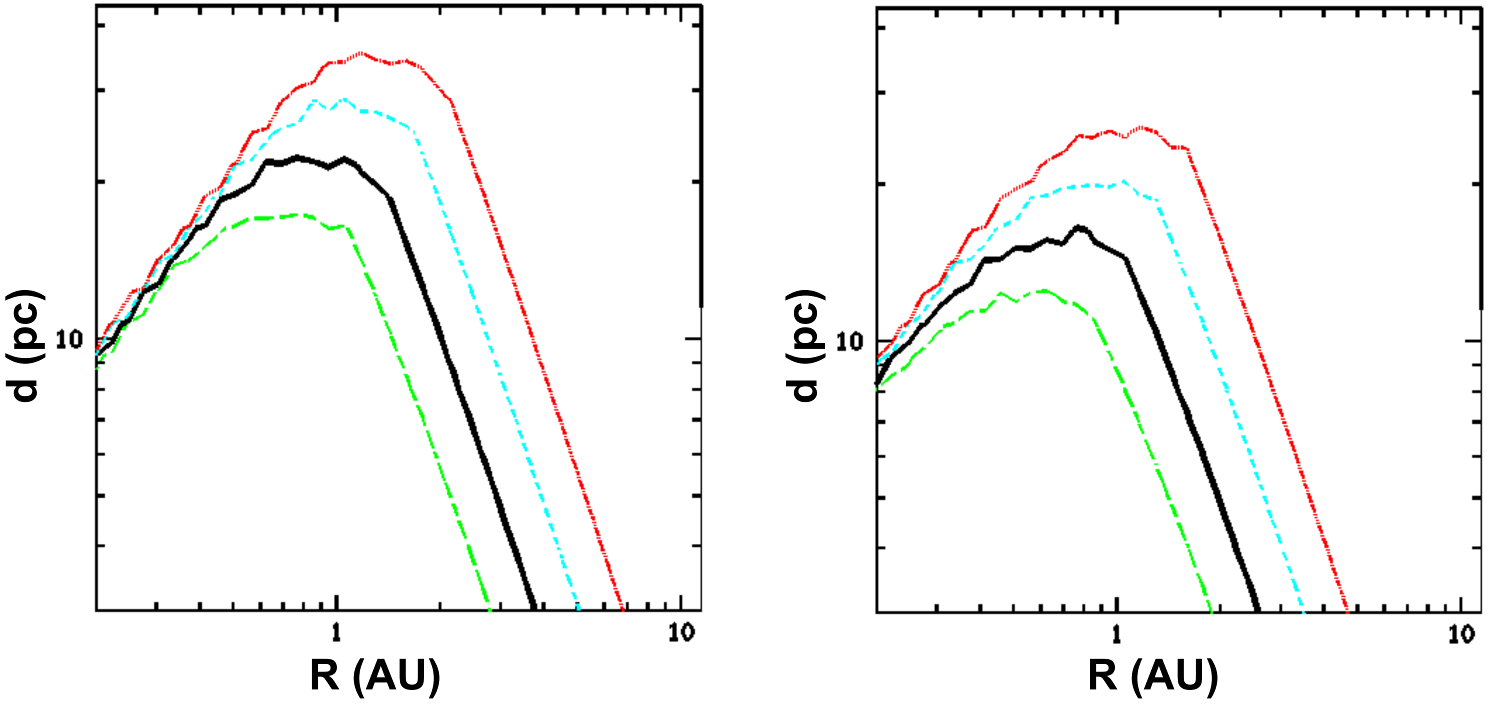
- Viewing geometries
  - Planet orbit inclination and period
  - location of TPF (if it varies)

NOISE AND CONFUSION FACTORS

- Brightness of star
  - Spectral passband observed
  - Type of star
  - Distance from us
- Angular separation of star and planet
  - Orbit radius
  - Distance from us
- Exozodiacal background in passband
  - Dust density distribution
  - Orbit inclination
- Local zodiacal background in passband
  - Location of TPF instrument
  - Ecliptic latitude observed
- Other backgrounds
  - Spectral passband observed

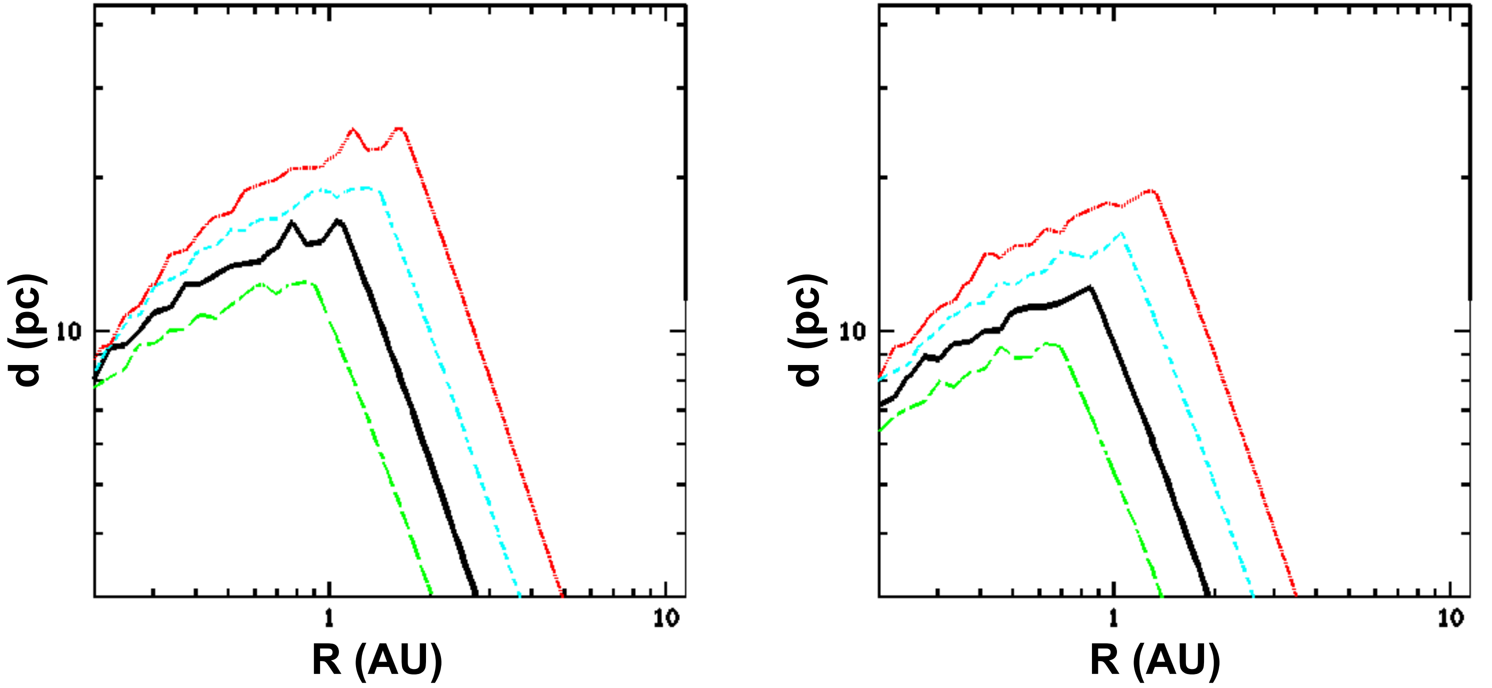
Spergel Coronagraph – Integration Times

- For a Spergel-pupil coronagraph with 8-m aperture, we show the integration times required for detection (SNR = 5) of an Earth mass planet (with albedo = 0.5 independent of wavelength) around a solar-type star and a K2 dwarf.
- The green, thick black, light blue and red lines are for 3000, 10,000, 30,000, and 100,000 second integrations. With a 10,000 second integration, we should be able to detect planets in the habitable zones out to 14 and 20 pc around K and G stars.



Spergel Coronagraph with Pessimistic Mirror-Control Estimate

With more pessimistic assumptions about our ability to control the mirror, these calculation for “Earths” near 10 pc solar-type and K2 stars assume we can only marginally control the mirror imperfections, so that the amount of scattered light from the star scales as 1e-10 $(1.1 / \lambda)^2$

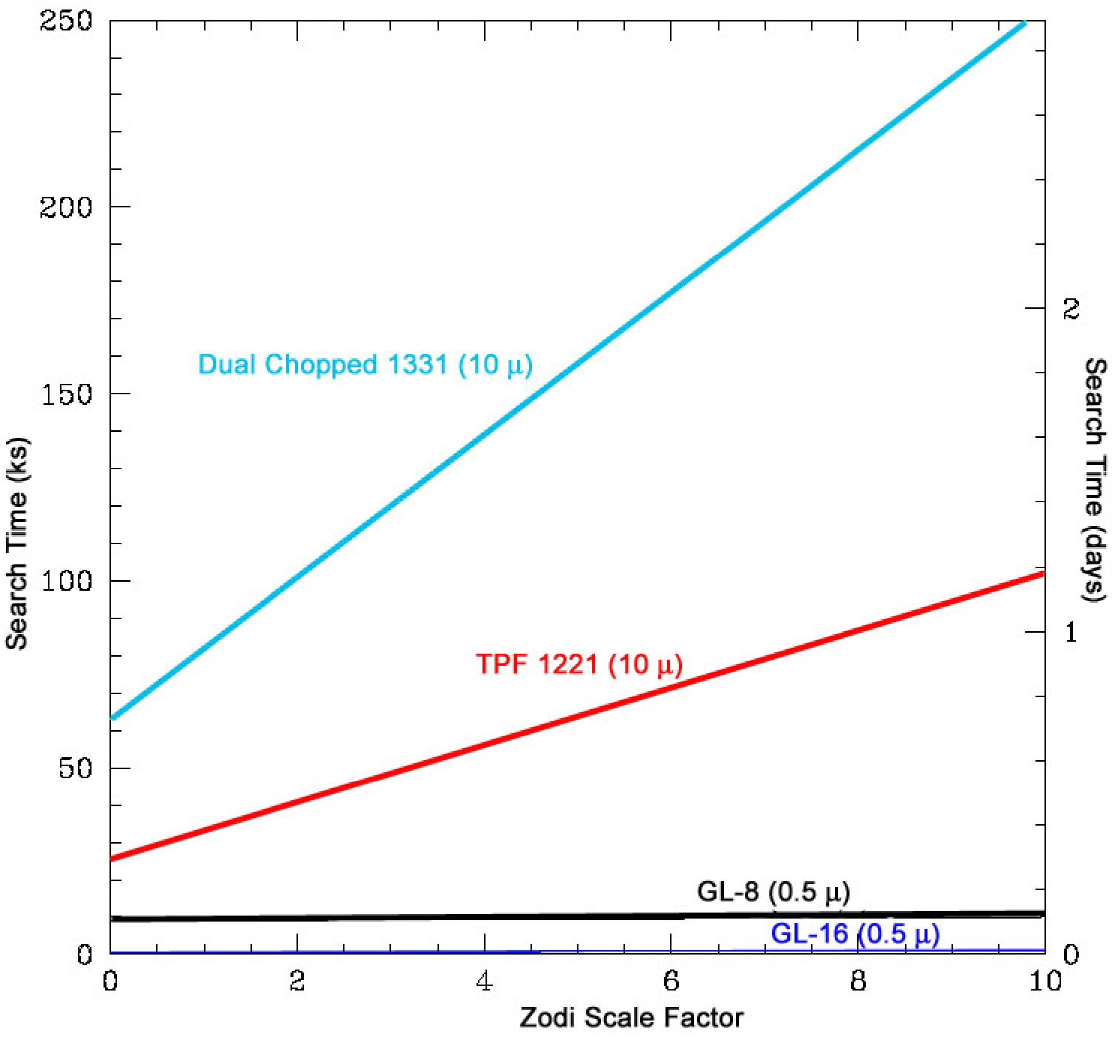


SNR Performance Depends on Zodi Levels

- SNR per unit time
  - Reflected-light architectures survey stars and characterize planets more quickly than emitted-light architectures
- MIR interferometers are a factor of 3 slower than an 8-m coronagraph for the same SNR, due mainly to zodi levels
  - Interferometer performance degrades much faster with increased exo-zodi levels
    - 10 x zodi = 10 x integration time (If both zodis were to disappear, the signal would be virtually pure planet, since nulling works so well (in theory at least)
    - The quantity of exozodiacal dust around other solar systems is poorly known. Ground interferometers will measure exozodis down to levels less than ten times our solar system.
  - A refined interferometer we should consider is the pupil densification version, which reduces some of the zodi contribution
- In the visible, zodis are roughly the same as the planet signal, but both are dominated by the diffraction leak and the scattered light from mirror ripple
  - But since total effective background in the visible is smaller than in IR, the visible wins in integration time

Planet-Finding Resilience to Exo-Zodi

- Time to detect an Earth in quadrature at 10 pc and 1 AU, for 2 thermal-emission and 2 reflected-light architectures
  - As a function of the exo-zodi multiplier, the "number of exo-zodis" at the target star
  - For a twin of our solar system, the multiplier is unity
- If several-zodi or greater, reflected-light systems have much smaller search times
  - Looking for exo-zodi dust, emitted-light architectures are the systems of choice
  - Looking for planets, reflected-light systems appear to be the ones of choice.



Illustrative Performance: Integration Times for 10 pc "Earth" at Quadrature, R = 3, SNR = 5

Architecture Option	λ , μm	IWD, mas	OWD mas	Airy rad., mas	Gaussian HW, mas	Lyot --	Pixel, mas	Integrat'n Time, Ks
Gauss-Lyot 8-m CG	0.3	50	2000	8	100	.80	10	50
(Collecting area 50 m^2)	0.5	50	2000	13	100	.71	18	10
	1.0	52	2000	26	104	.45	58	23
	2.0	104	2000	52	208	.45	116	180
Gauss-Lyot 16-m CG	0.3	50	2000	4	100	.85	5	4
(Collecting area 200	0.5	50	2000	7	100	.80	9	1
	1.0	50	2000	13	100	.71	18	1
	2.0	50	2000	26	100	.41	63	12
TPF 1-2-2-1 Un-chopped IF	7	18	270	19	–	--	--	93
3.5-m x 75-m B/L (Area=38 m^2)	10	26	390	27	–	--	--	33
	20	52	780	55	–	--	--	83
Dual 1-3-3-1 Chopped IF	7	16	270	19	–	--	--	230
3.5-m x 75-m B/L (Area=58 m^2)	10	22	390	27	–	--	--	83
	20	44	780	55	–	--	--	200

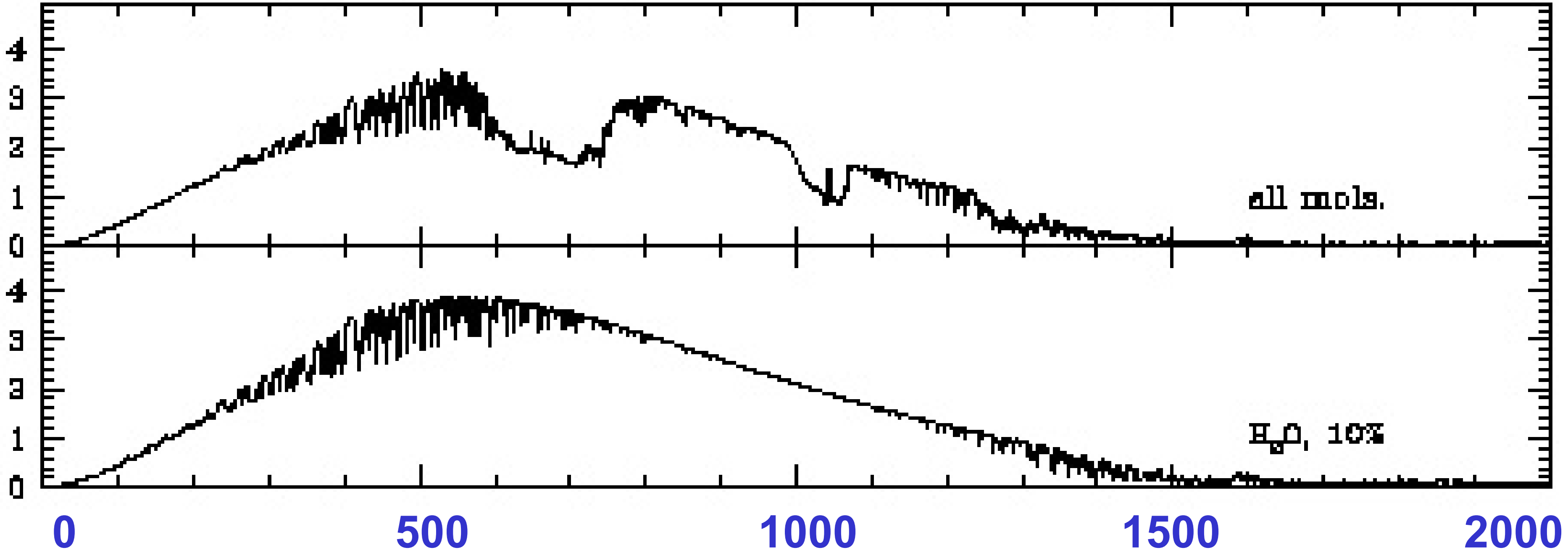
Biomarkers in the Two Wavelength Regions

- Both MIR and Visible/NIR information quality for big-picture science
  - IR and the visible are almost EXACTLY COMPARABLE in terms of what you can learn about life and how easily you can learn it
    - Only indicator of life in the IR at low spectral resolution is O_3
    - Only indicator at low spectral resolution in the visible is O_2
  - Auxiliary indicators (temperature, albedo, clouds vs. rock, chlorophyll, etc.)
  - Secular (temporal) variations
- We know the gases and absorption bands present in Earth's atmosphere
  - This does not rule out other gases, or tell in what ways an oxygenated, alien biosphere would be different from our own
  - CH4 is a possible bioindicator for an anoxic early-Earth, but N_2O shouldn't be there because it photolyzes rapidly in the absence of O_2 and O_3
- A stronger criterion for life is simultaneous presence of O_2 plus a reduced gas – CH_4 or N_2O, indeed a stronger signal for life
  - Hard for TPF: CH_4 & N_2O lines very weak in today's atmosphere
  - CH_4 should be easily detectable in visible or IR in an anoxic atmosphere, so is a potential indicator for life prior to rise of O_2 in planet's atmosphere

Biomarkers in an Expected Typical Infrared Spectrum

(a) A thermal emission spectrum calculated for the present whole Earth, including all known significant molecular species, is shown in the top panel. The model atmosphere uses realistic vertical profiles of temperature, pressure, and species abundances.

(b) Water vapor. The far-infrared rotational lines appear on the left at small wavenumbers, and the 6-micron vibrational band appears on the right at high wavenumbers.



The abscissa is in units of cm^{-1}, so a wavelength of 10 microns is at 1000 cm^{-1}.
The ordinate is in units of 10^{14} Janskys/steradian.

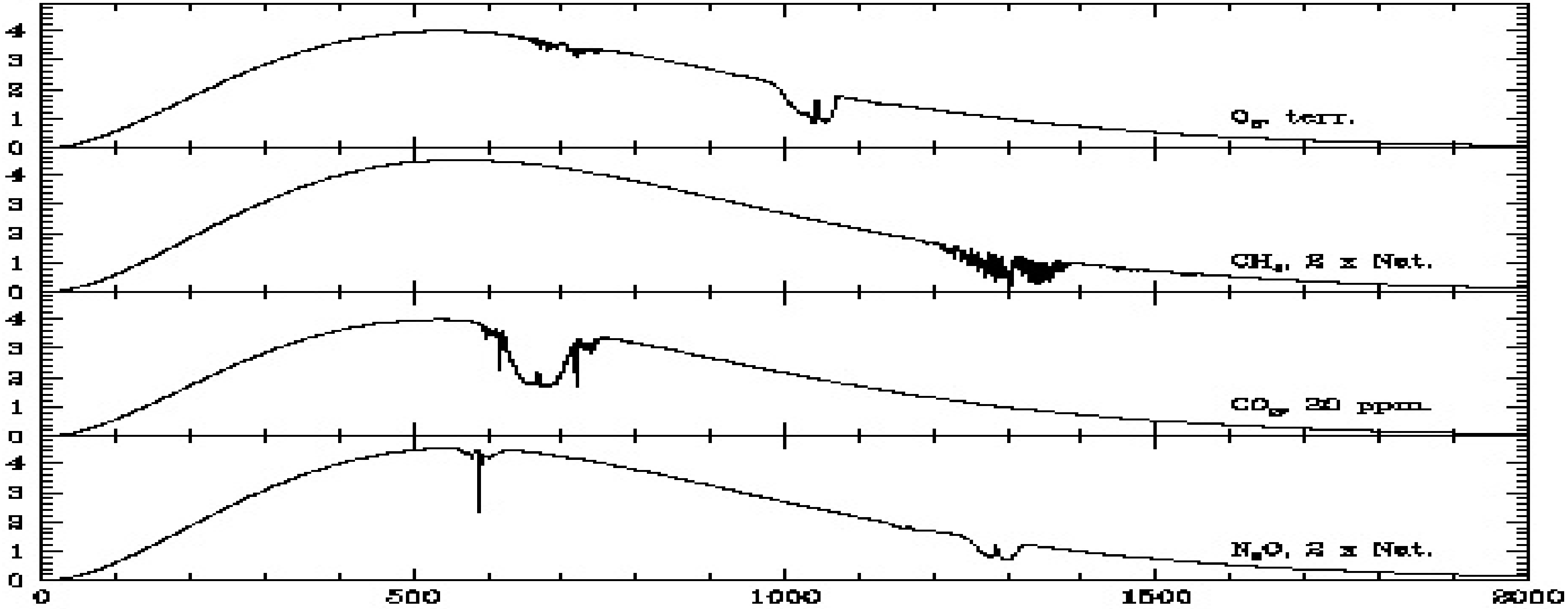
Other Potential IR Spectral Biomarkers

(a) Ozone is shown in the top panel, at normal terrestrial abundance, with the well-known 9-micron band as its strongest feature, and a weaker 16-micron band which is probably not useful because it will be masked by carbon dioxide. There are no significant O_2 lines in the infrared.

(b) Methane appears next, increased to 2 times natural abundance, to make the features more readily apparent. The methane signature band is centered at about 7.7 micron wavelength.

(c) Carbon dioxide comes next, shown at a mixing ratio of 20 parts per million, much less than the nominal present value of about 360 ppm. Note the prominent 16-micron feature.

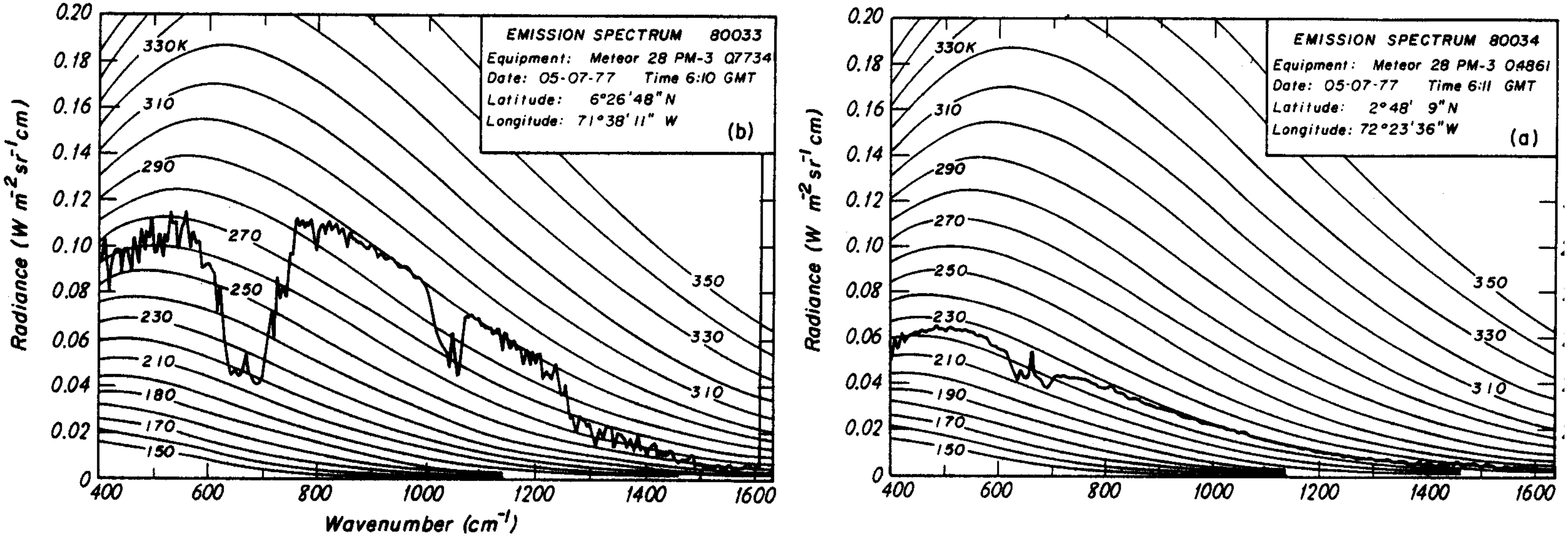
(d) Nitrous oxide is at twice natural abundance, and the most prominent feature is centered at about 7.8 microns, nearly overlapping the methane feature, and on the edge of 6-micron band of water.



MIR Spectral Biomarkers Hard to See if Cirrus Clouds Dominate Planet’s Atmosphere

Cirrus clouds could just about completely damp out the signal of H_2O and O_3

- Only the center part of the CO_2 15-µm band remains
- Cirrus clouds are high and cold, so background radiation from them masks absorption bands
- We expect Earth-like planets generally with at most 50% cloud cover (a condensation process)
  - (Clouds on Venus and Titan form photochemically, and 100% cloud cover is the rule)



Observed radiance spectra for (a) cloudless and (b) cirrus conditions obtained from METEOR satellites (after Spanküch and Döhler, 1985); from Kuo-Nan Liou's Radiation and Cloud Processes in the Atmosphere, p293.

Biomarkers – Visible/NIR Spectrum

(a) A reflection spectrum calculated for the present Earth, normalized to unity, based on realistic vertical profiles of temperature, pressure, and species abundances.

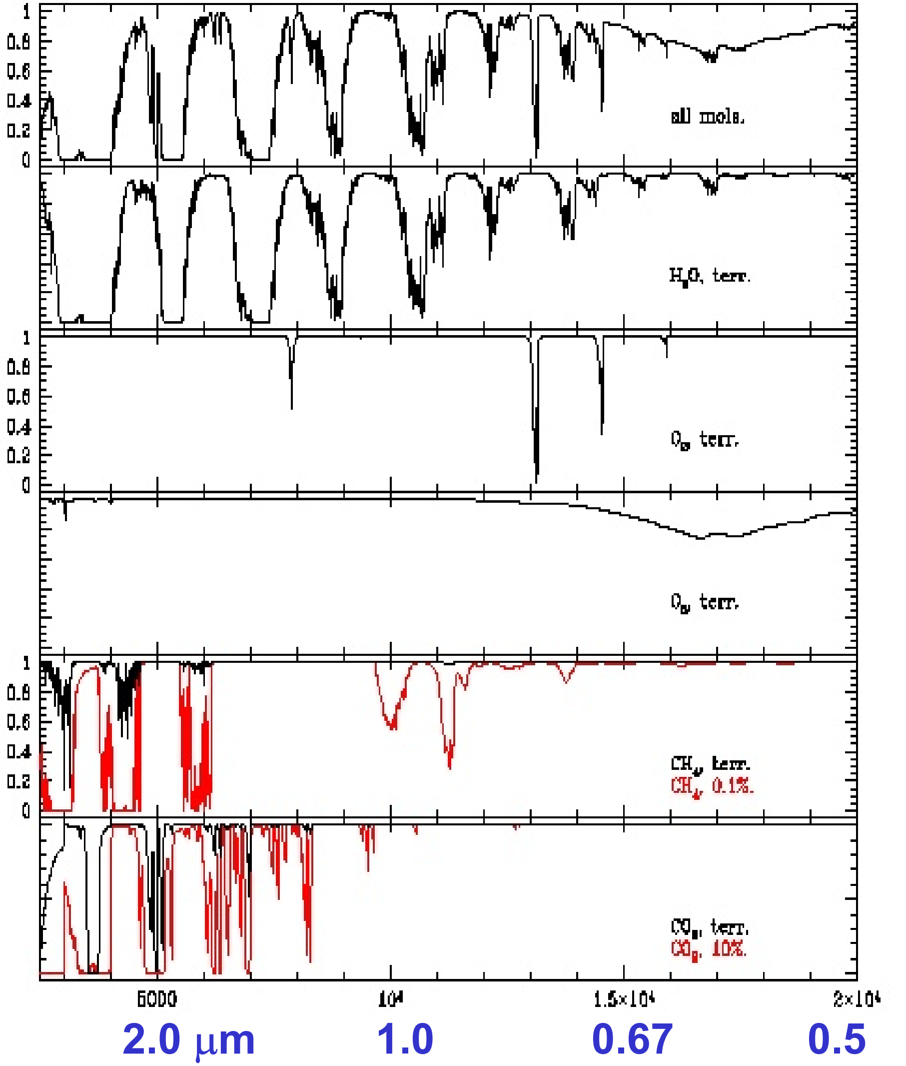
(b) Water vapor bands start in the visible and march toward longer wavelengths. Astronomical J, H, K, and L (partial) bands are reflection windows on the left.

(c) Oxygen, A-band at 0.76 micron the strongest feature.

(d) Ozone, with the broad band near 0.6 micron and strong at about 20 percent depth. Extremely strong ultraviolet bands have a cut-on of about 0.32 micron.

(e) Methane, at both terrestrial abundance (1.6 ppm, black) and at an enhanced abundance produced by a methane burst (0.1 percent, red) such as is believed to have occurred in the Earth's past. A low-abundance feature is at 2.3 microns. High-abundance features are at 0.9, 1.0, and 1.7 microns.

(f) Carbon dioxide, at 2.0 and 2.8 microns (overlapped by water). Early Earth's carbon dioxide is believed to have gone up to10 percent, producing a large greenhouse effect. The corresponding spectra are shown in red.



Biomarker Detectability Comparison

- *As shown in the table on the following page, we studied spectral signatures and integration times needed to detect 6 potential biomarker chemicals*
  - Planet was assumed to be at 10 pc, like Earth 1 AU from a Sun, at quadrature
  - Illumination was half the planet in the visible, the full disk glowing in the MIR
- Integration-time performance was evaluated for four architecture options:
  - Gauss-Lyot Coronagraphs: 8-m and 16-m aperture primary mirror diameters
  - MIR interferometers: TPF booklet design and Chopping Dual-DAC
- Chemical atmospheric concentrations were set equal to the present value on Earth
  - In addition, one column in the table has entries for a "methane burst" of 600 x its present concentration on Earth, which is thought to be a value Earth once had
- For most of the species the coronagraphs work faster or as fast
  - Only for CO_2 do the interferometers work faster, but CO_2 is more a measure of the presence of an atmosphere than a high-priority biomarker
  - For present Earth concentrations of CH_4 and N_2O all architectures are too slow to be practical
- *A well-designed spectrometer system can measure the species in parallel so the complete characterization time is set by the longest integration time*

Biomarker Integration Times

Time to detect at SNR=5, Earth at 10 pc

Biomarker	O_2	O_3	H_2O	CH_4	CH_4	CO_2	N_2O
abundance	1x = 21%	1x = 6 ppm	1x = 0.8%	1x =1.6ppm	600x= 0.1%	1x=350ppm	1x=.33pmm
wavelength	0.76 *um*	0.59 *um*	1.00 *um*	2.38 *um*	0.89 *um*	2.00 *um*	-
G-L, 8-m	810 ks	220 ks	82 ks	22000 ks	560 ks	4000 ks	-
	9 days	3 days	1 day	260 days	6 days	50 days	-
G-L, 16-m	48 ks	18 ks	4 ks	1500 ks	28 ks	270 ks	-
	0.6 days	0.2 days	0.04 days	18 days	0.3 days	3 days	-

Biomarker	O_2	O_3	H_2O	CH_4	CH_4	CO_2	N_2O
abundance	1x = 21%	1x = 6 ppm	1x = 0.8%	1x =1.6ppm	600x= 0.1%	1x=350ppm	1x=.33pmm
wavelength	-	9.6 *um*	28.8/6.9 *um*	8.1 *um*	8.1 *um*	15.2 *um*	7.8 *um*
TPF 1221	-	625 ks	266 ks	50000 ks	625 ks	151 ks	16000 ks
	-	7 days	3 days	570 days	7 days	2 days	190 days
Dual 1331	-	1600 ks	640 ks	123000 ks	1400	240 ks	41000 ks
	-	18 days	7 days	1400 days	16 days	3 days	470 days

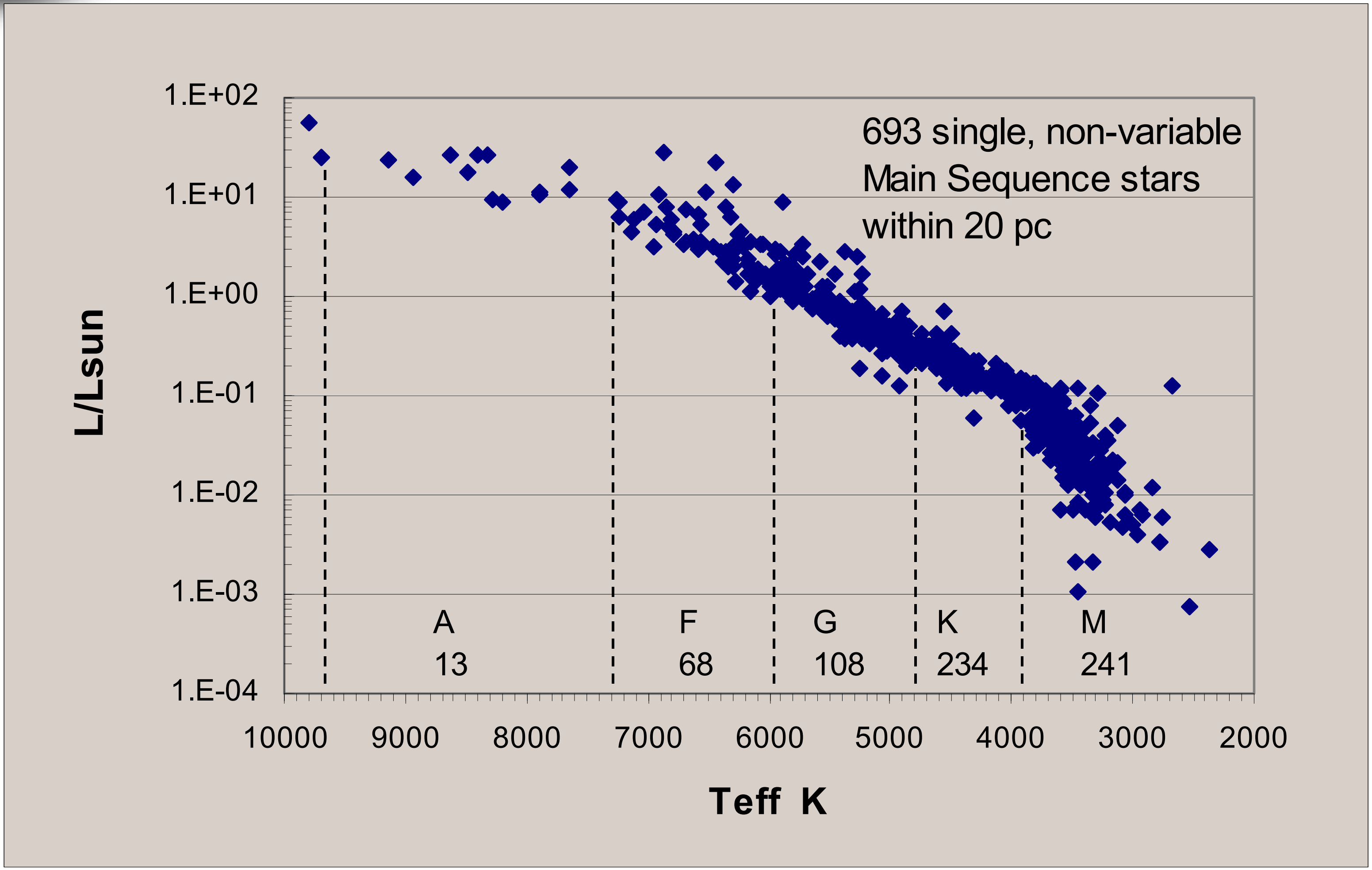
Star Sample Study: Actual Phenomenology Guides TPF Systems Engineering

- Goal – find and characterize Earth-like planets in HZ of a sample of stars
- What requirements does this place on an observatory?
- Most studies have considered Earth-sun analog systems at 10 pc distance
  - Good for initial estimate of geometric and radiometric requirements
- Data are available to analyze actual population of candidate target stars and to establish observing requirements from scientific objectives
  - Volume-limited sample – 10 pc, 20 pc, ??
  - Limited range of spectral types – F0 - K9, F5 - K5, ??
  - Limited star classes – non-binary, non-variable, no white dwarfs or giants
  - Range of distances between star and planet (within habitable zone)
  - Range of planetary properties
    - Radius
    - Mass
    - Albedo

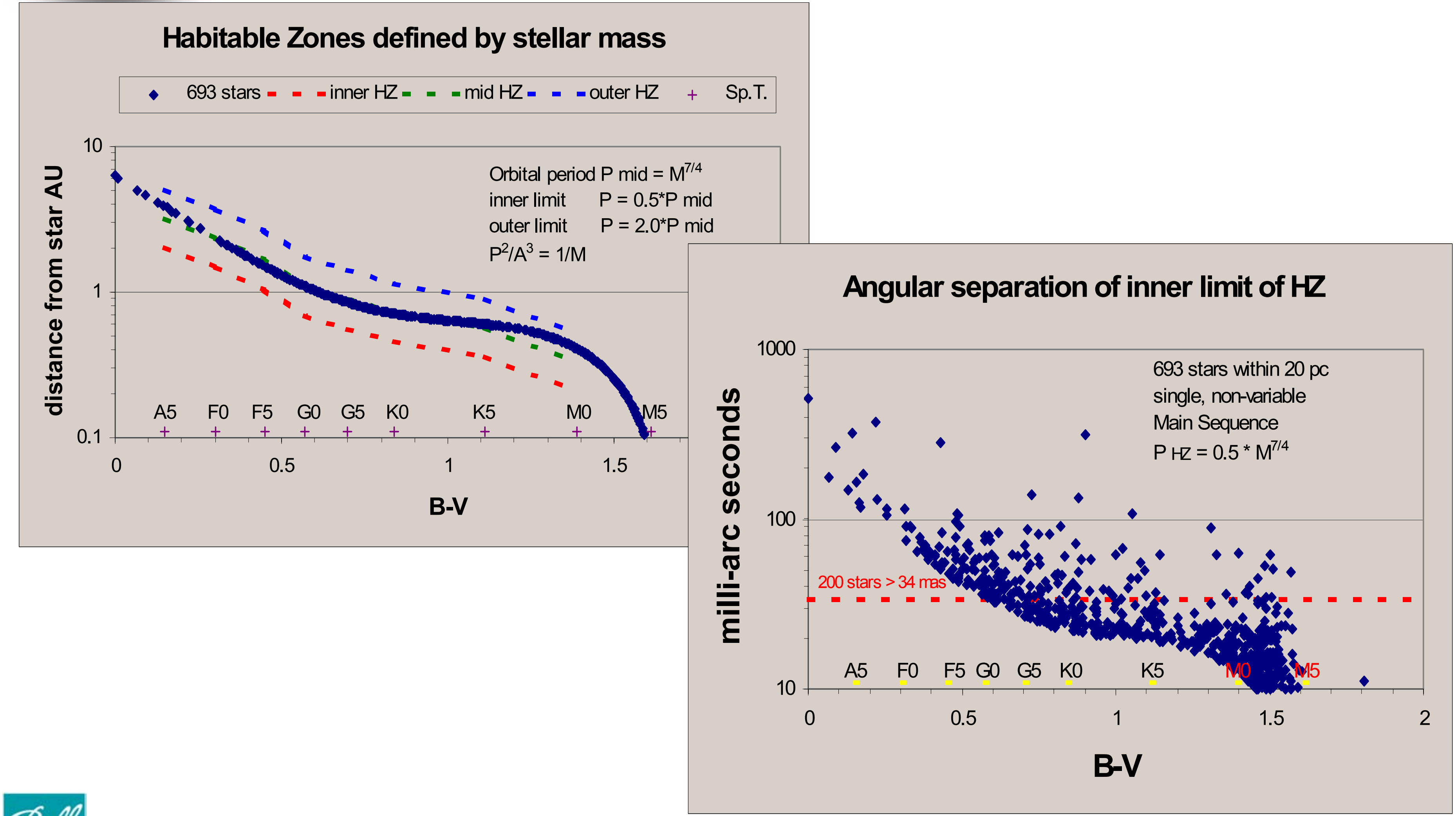
Star Sample Analysis Approach

- Sample population from Hipparcos main catalog, parallax, and B-V color
- Limited to single, non-variable, main-sequence stars
- Inferred stellar parameters from textbook relationships
- Constructed H-R diagram
- Derived HZ from Kasting planetary model atmospheres and correlation with stellar parameters
- Computed angular separations for inner, mid, and outer limits of HZ
- Estimated planet brightness in reflected light (V band)
- Estimated planet brightness in emitted thermal radiation (N band)
- Examined distributions, correlations, trends

Hertzsprung-Russell Diagram Shows Local Stellar Spectral Types



Habitable Zone Dependence on Stellar Properties and Distances



Habitable Zones defined by stellar mass

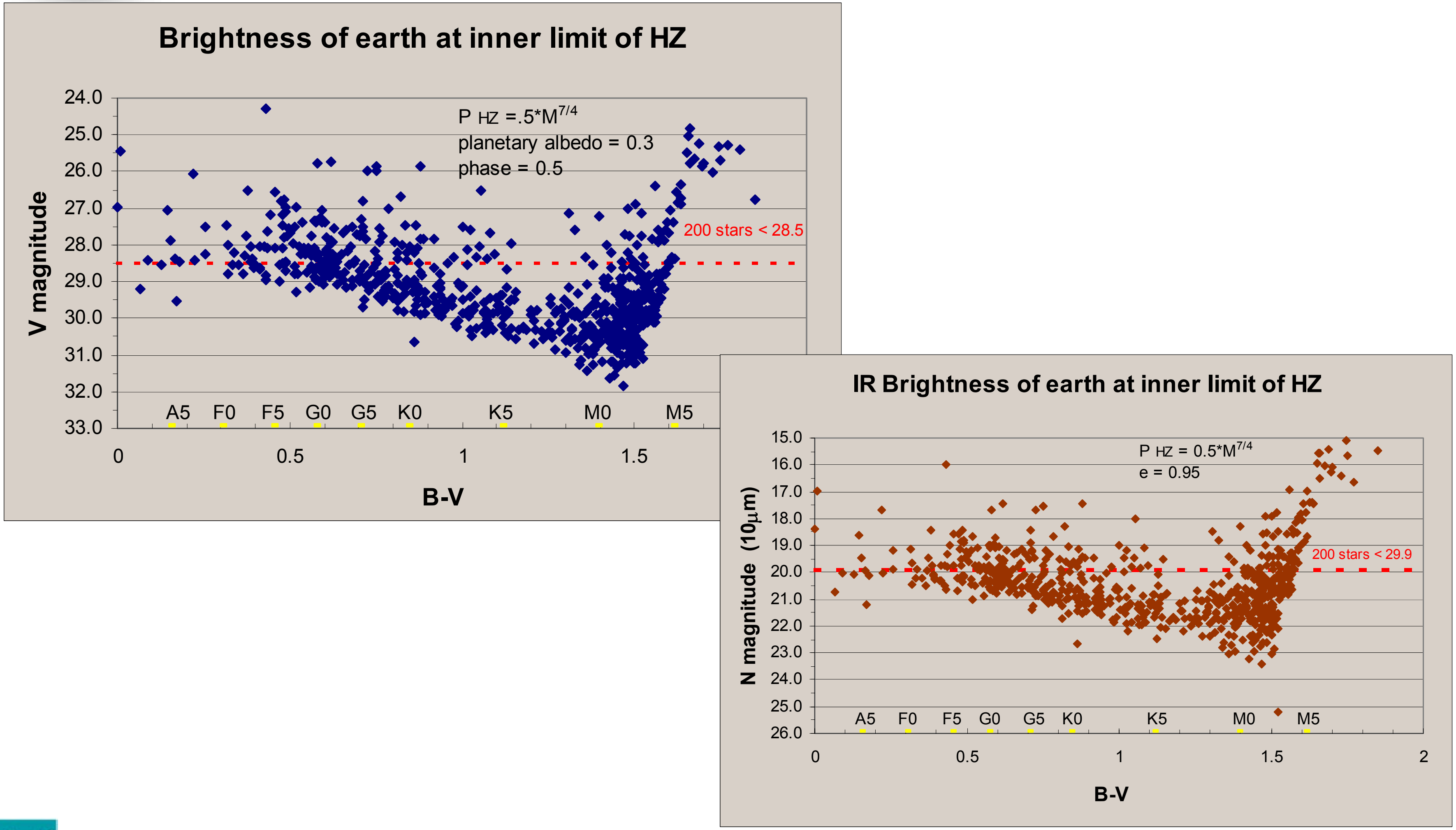
Orbital period P mid = $M^{7/4}$
inner limit P = 0.5*P mid
outer limit P = 2.0*P mid
$P^2/A^3 = 1/M$

Angular separation of inner limit of HZ

693 stars within 20 pc
single, non-variable
Main Sequence
$P_{HZ} = 0.5 * M^{7/4}$

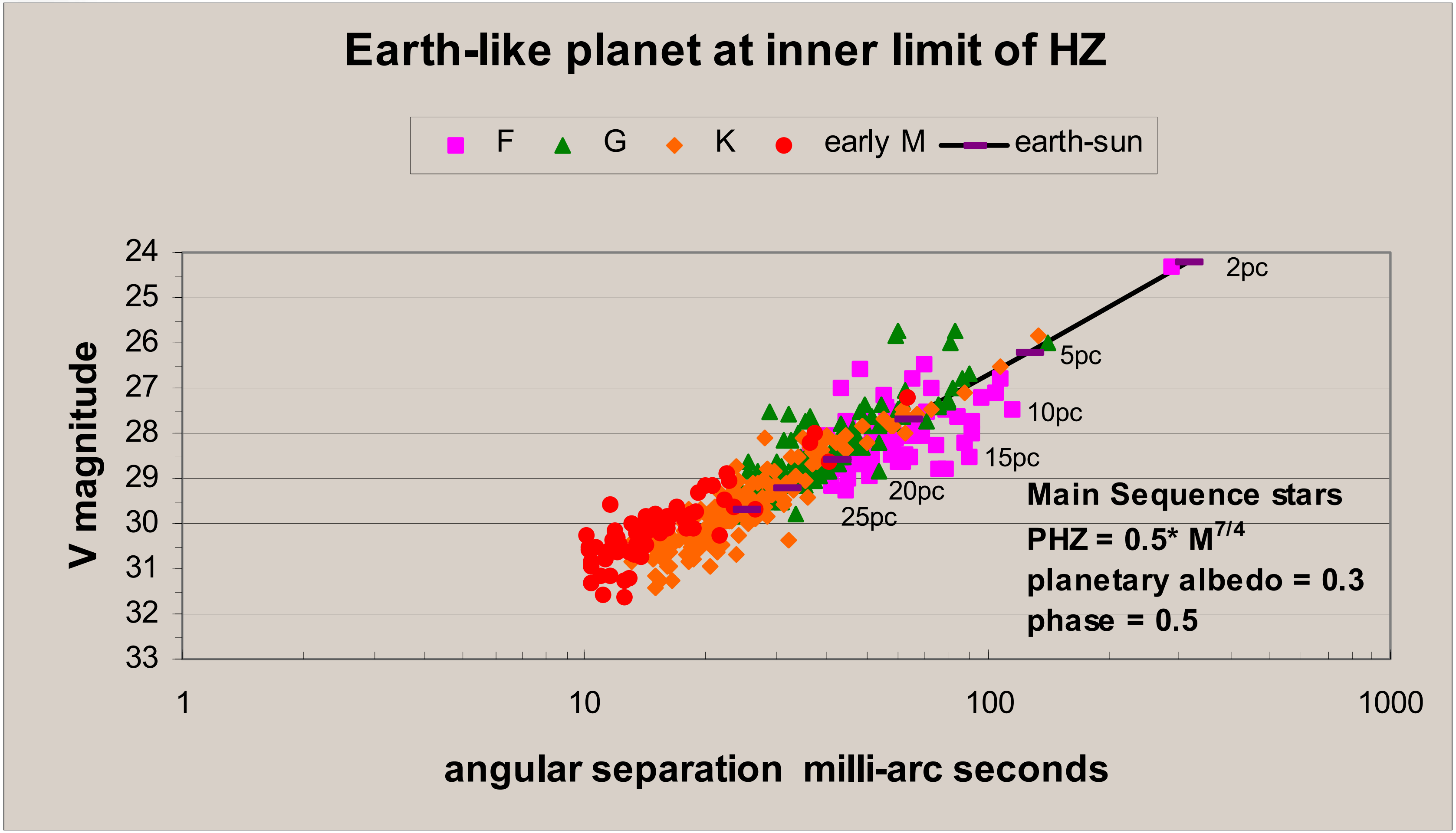
200 stars > 34 mas

Planet Brightness at Inner Edge of HZ, Reflected and Emitted Light

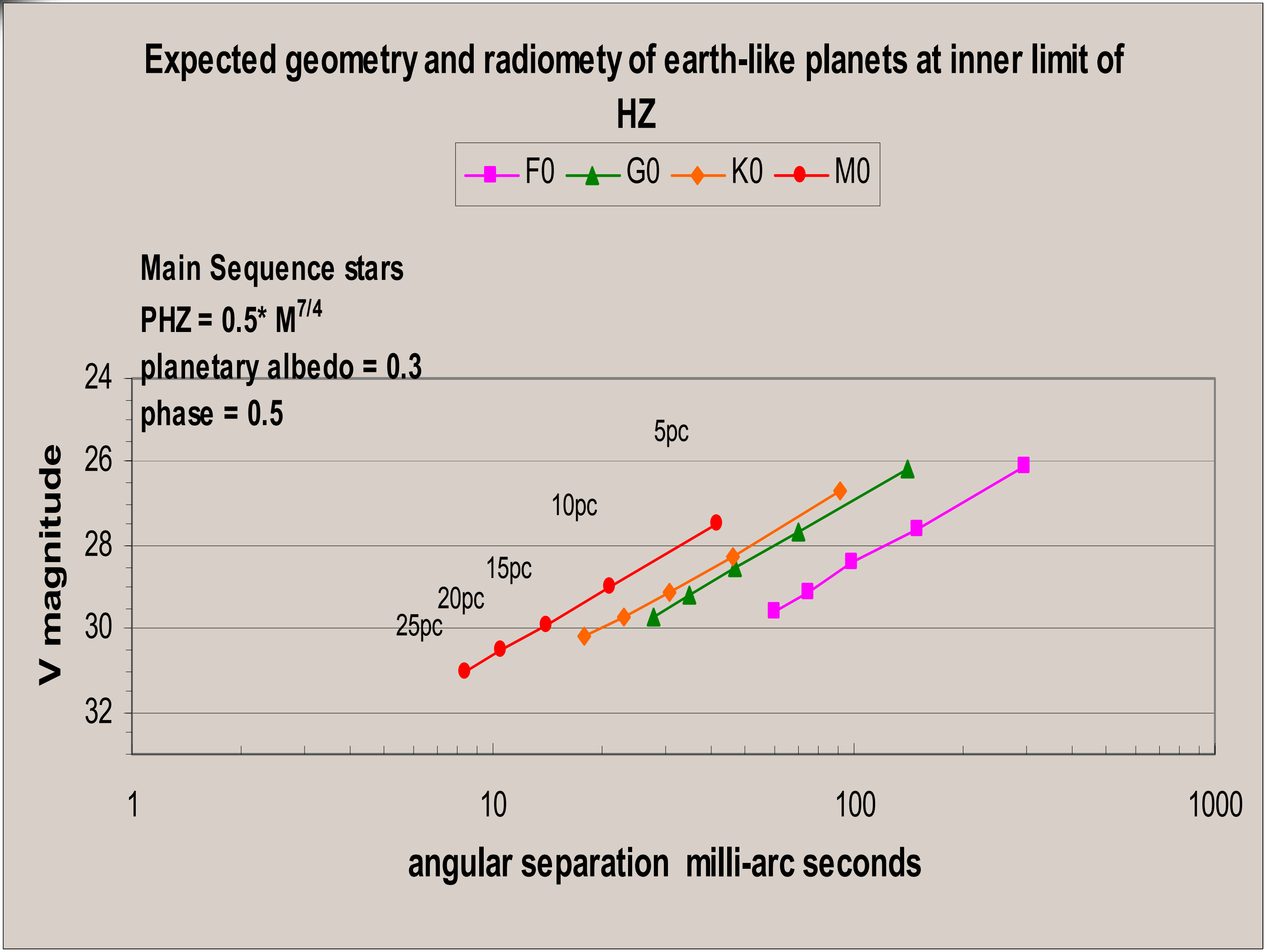

Brightness of earth at inner limit of HZ

IR Brightness of earth at inner limit of HZ

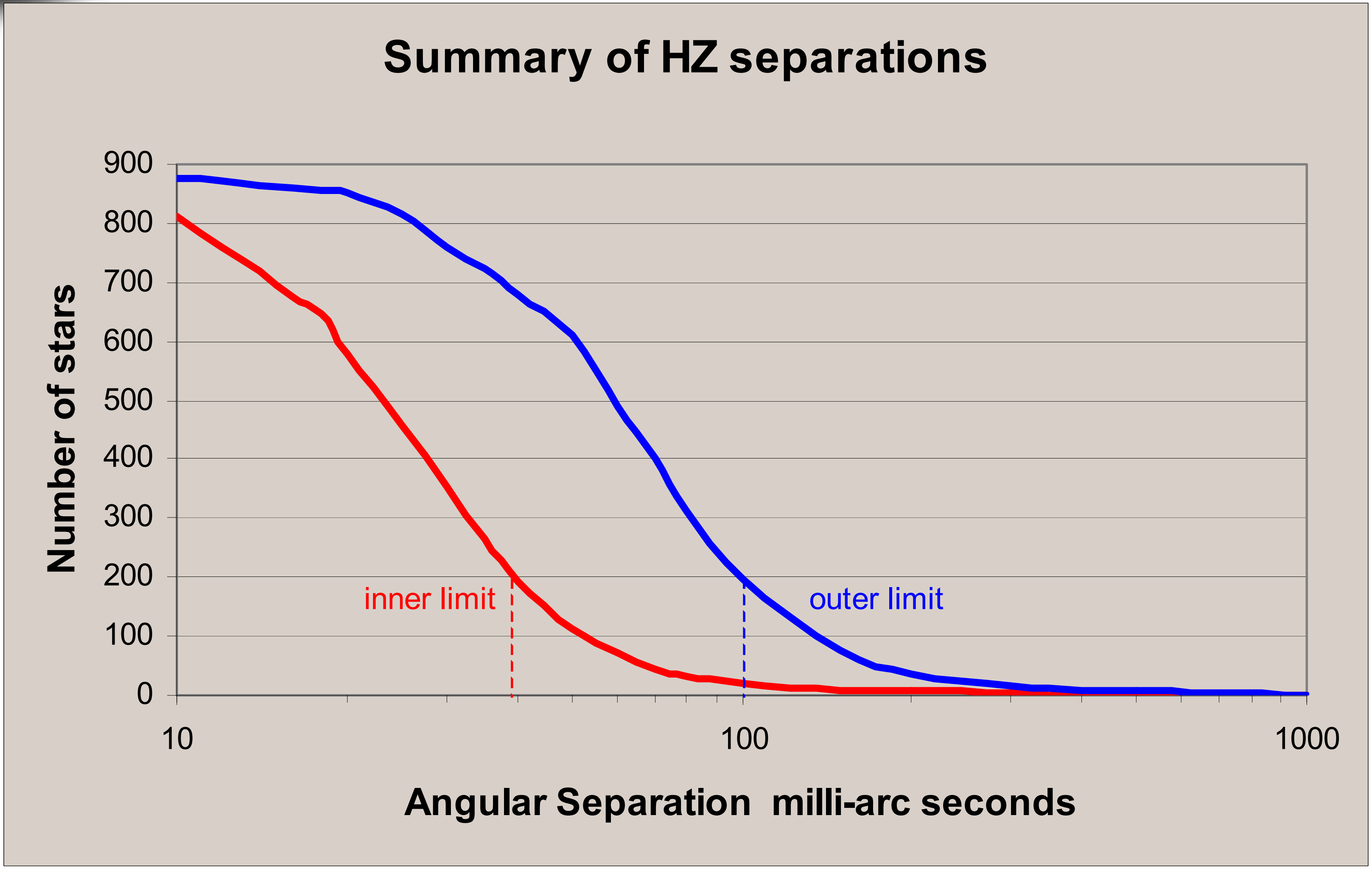
Planet Brightnesses and Angular Separations Define TPF Performance Space



Brightnesses and Angular Separations for Limiting TPF Planet Cases

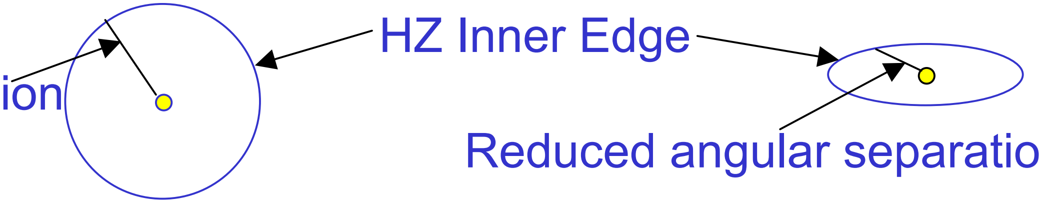


Covering the Habitable Zones of Many Stars Requires Small Inner Working Distances



Inclination Effects on IWD

- Expected exoplanetary orbit planes frequently highly inclined to sky plane
- Star-HZ angular separations would thereby often be greatly reduced:



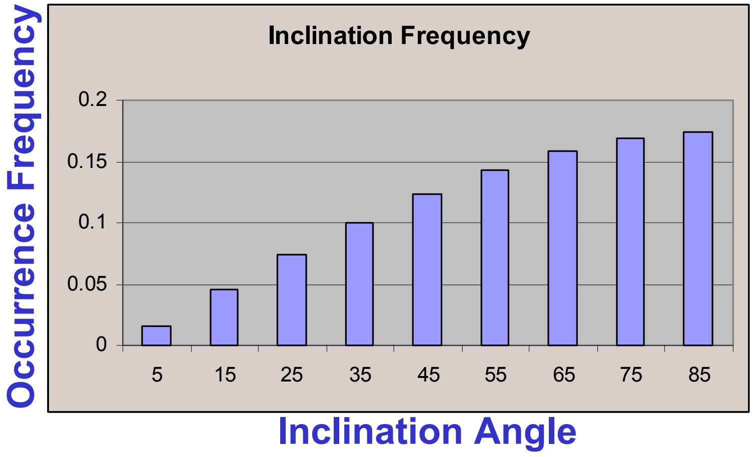
System Appearance: **Face-On** **Highly-Inclined**

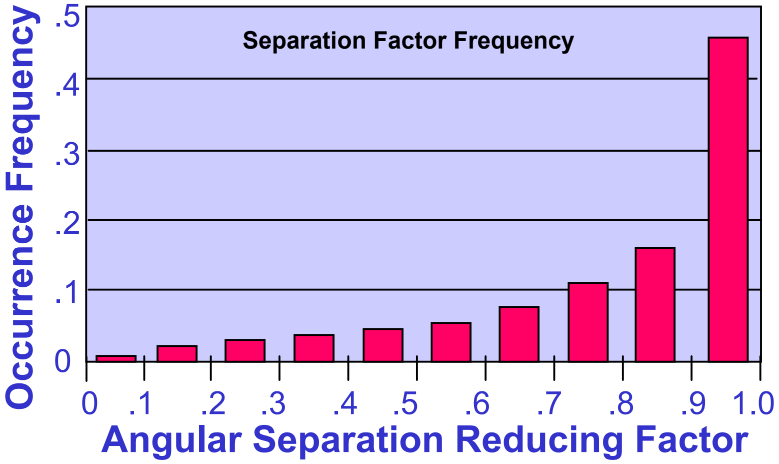
HZ Inner Edge

Full angular separation

Reduced angular separation

- Analysis – this is not a big concern: 70% of the time, sep. > 0.7 max. sep.





Fundamental Geometry Result – TPF Needs to Achieve a Very Close IWD

- We studied the actual nearby stars in the Hipparcos catalogue, their luminosities and spectral types (which determine the HZ), and distances
- The hardest place to view a planet in an HZ is at the HZ inner edge
  - Starlight leakage and exozodi are highest there, even though planet is bright
    - Leakage there varies steeply with orbital radius, as does exozodi
  - Therefore we determined the angular sizes of the HZ inner edges
- Thus detectability of planets at the HZ inner edge is one criterion for ensuring that we can see planets throughout the HZ for that star
- The result is that to see the inner HZ around at least 150 suitable FGK stars, we need an effective Inner Working Distance(IWD) of 35 mas
- For each architecture and observed wavelength passband, a given IWD demands a certain minimum aperture or baseline for adequate stellar leakage suppression
- Comparing visible-light coronagraph to emitted-light interferometer designs
  - Interferometers decrease their IWD simply by increasing their baselines
  - Since coronagraphs seem to achieve SNR more quickly, by factors > 3, they could increase integration times and operate at smaller IWDs than the typical 5 Airy radii

Architecture IWD Considerations

- For a coronagraph it's more difficult to achieve an IWD at longer wavelengths
  - Longer NIR and biomarker spectral features (e.g., 2 μm methane) are harder to reach

- For interferometers, a shorter nominal baseline minimizes star leakage
  - A nominal baseline, ~ 45 m full length, gives ~34 mas at $\lambda = 10$ μm
  - The longest baseline for sensitive nulling, ~ 150 m, gives an IWD ~10 mas at 10 μm

- The Chopped Dual Bracewell suffers greatly from star leakage
  - It needs a very short baseline to be competitive in SNR

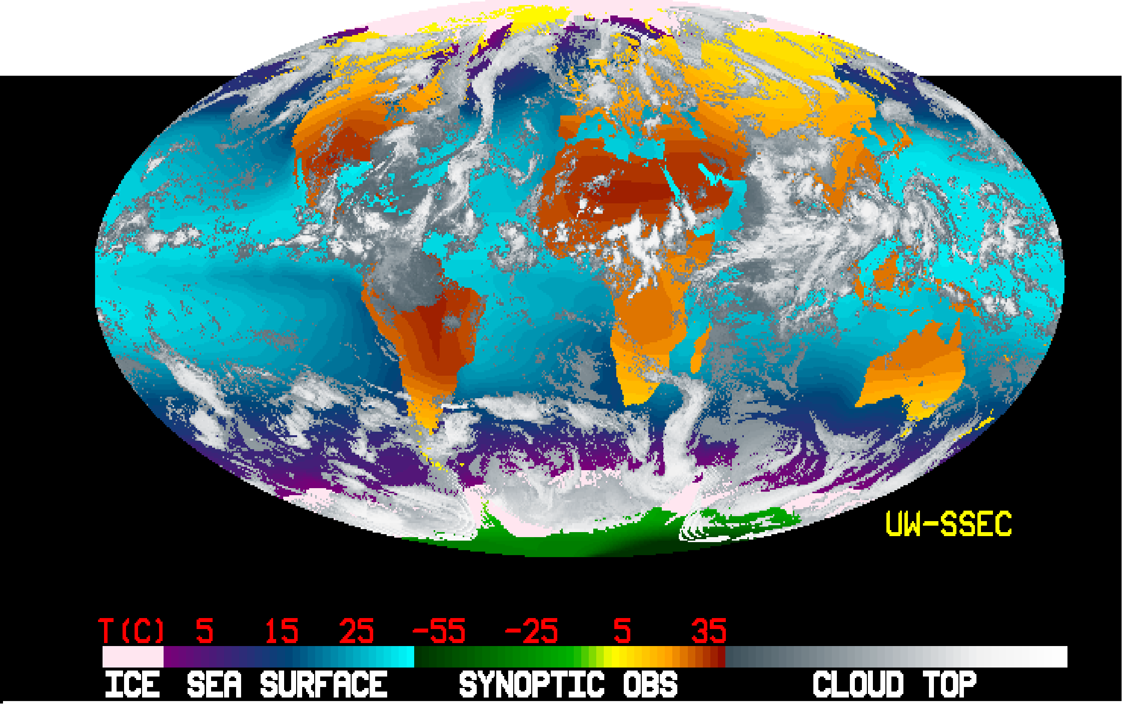
- A Chopped Dual DAC (C-D-DAC) is preferable: it's zodi/exozodi limited, and in the 4-collector version its stripe-placement arithmetic is like the C-D Bracewell
  - C-D-DAC example: λ = 6μm, full length ~ 150 m (IWD ~ 7 mas)
    - Star leakage contribution reaches 1e-6, and climbs as L^4 from there
    - Star leakage can probably be tolerated at levels generally a bit higher than 1e-6

Time Needed for the Exoplanet Mission

- Collecting area 50 m^2, visible-band, yields 1 planet photon in 2 minutes
- Observe each star at least 8 times over a few years of a TPF mission
  - Compensates for 30% of time planets may appear too close to star
  - Still allows ~ 5 real detections & measurements of each planet present
- Time to carry out the planet-finding observations:
  - 9 hours to carry out one contiguous set of observations on one typical star
  - Prior knowledge of exozodi disk angle can reduce observing time for a set
  - 1 hour to re-point telescope (easier if just one collector) to a new star
  - Planet-finding mission alone will require up to 80 hours per star
    - **A maximum of 500 days (1.4 years) to search 150 stars for planets**
- Time needed for spectra depends on how many planets actually found
    - If 50 good planets, could observe spectrum of each for total 9 days (when each in best ephemeris position, views spread to seek secular variations
    - Planet characterization program would occupy 450 days, or 1.2 years
    - This would leave 2.4 years, half of a 5-year TPF mission, for astrophysical measurements. (For the MIR IFs, no time is left for astrophysics.)

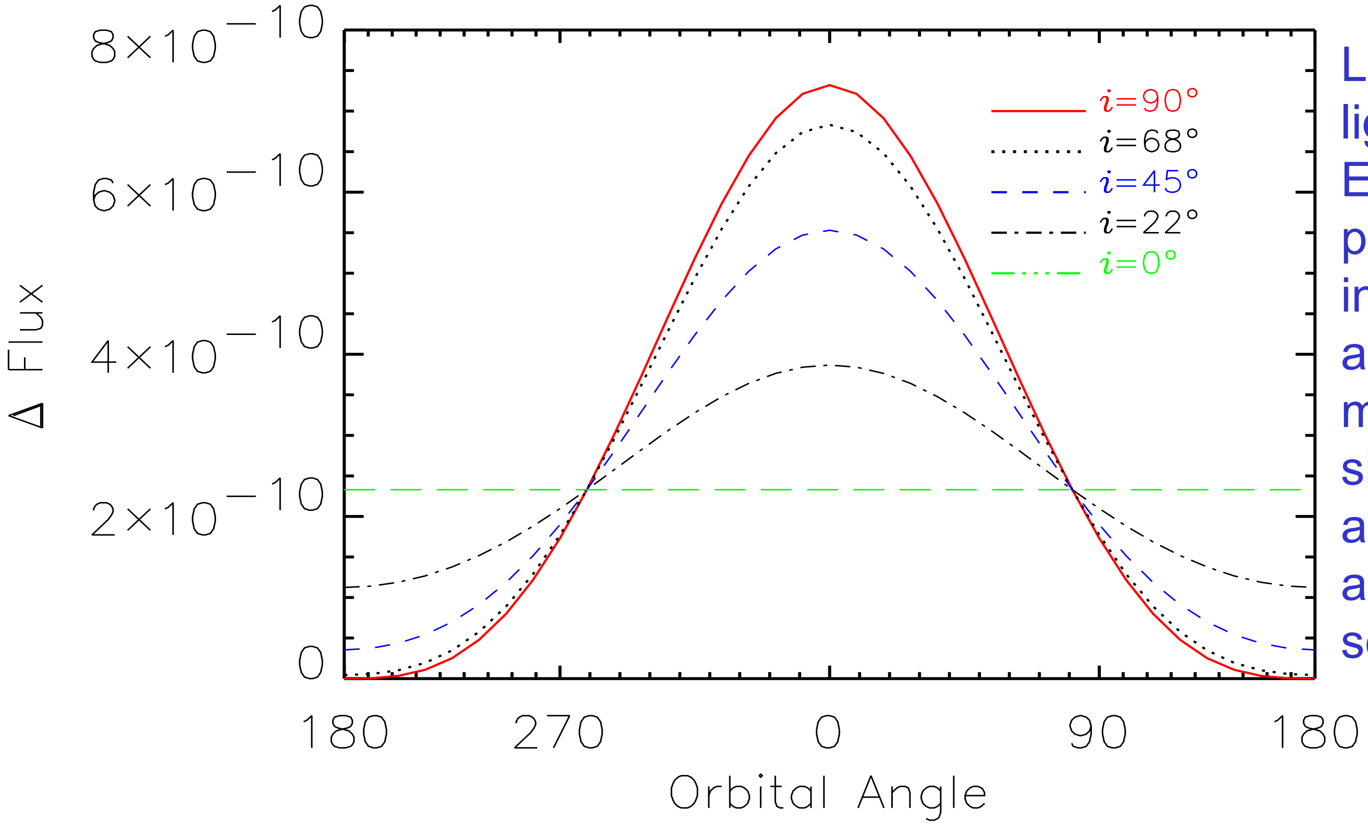
Secular (Temporal) Variation

- Spectra will vary because of cloud variation, seasonal variation and rotational period; <u>useful information might be derived from these variations</u>
- Optical: all flux has been scattered from the ground or clouds
- IR is more complicated because the temperature varies with season and day/night cycle and only certain wavelengths get from the ground to space



Yearly Optical Variation

- Planet goes through phases as seen from Earth over the course of an extrasolar planet year
- Light curve depends on orbital inclination of the system and on size and composition of scattering particles

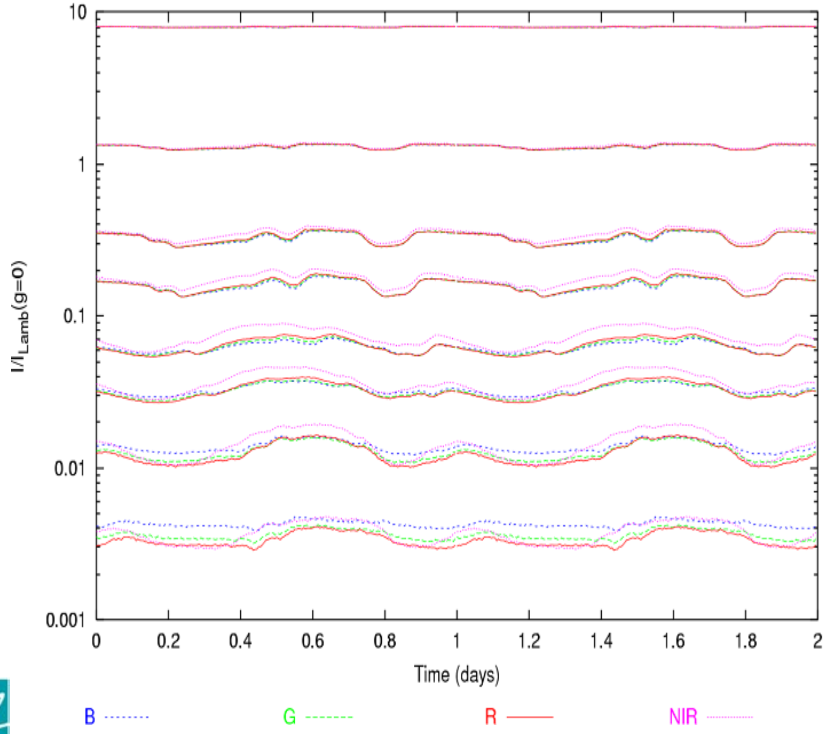


Lambert sphere light curve for an Earth-sized planet at different inclinations with albedo = 0.4. This makes the simplistic assumption that all parts of Earth scatter alike.

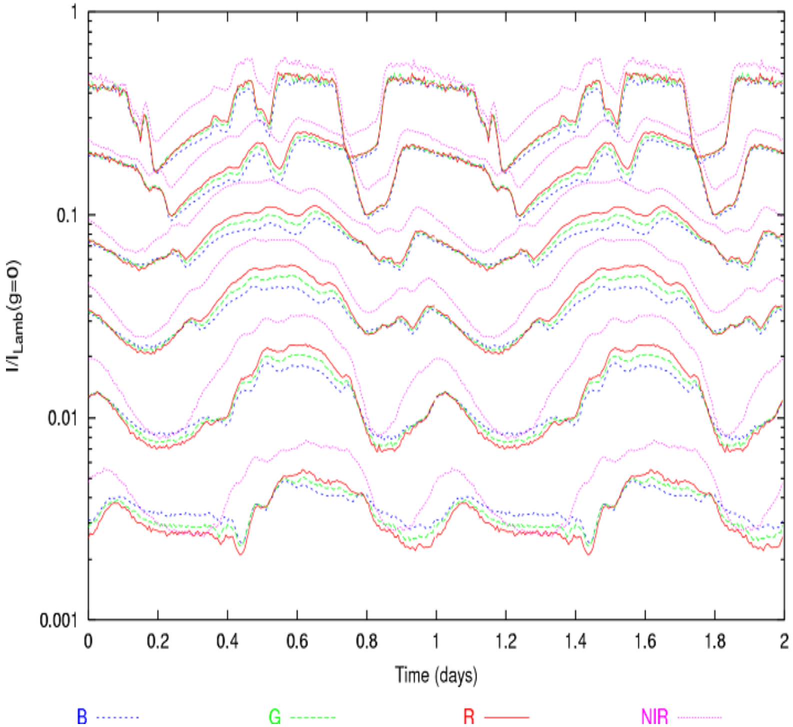
Daily Optical Variation

- Analysis of photometry due to daily variation may provide info on:
  - Rotation – Weather – Oceans – Land fraction – Ice cover (and ice age)
- Daily light curves for different phase angles of a simple model of Earth in 4 different colors (B=450nm, G=550nm, R=650 nm, NR=750 nm)
  - A model Earth based on satellite imagery and one degree resolution with distinction between: water, permanent ice, seasonal/sea ice, bare ground, ground with grass or brush, forest

Daily Light Curves for Earth with Constant Cloud Cover

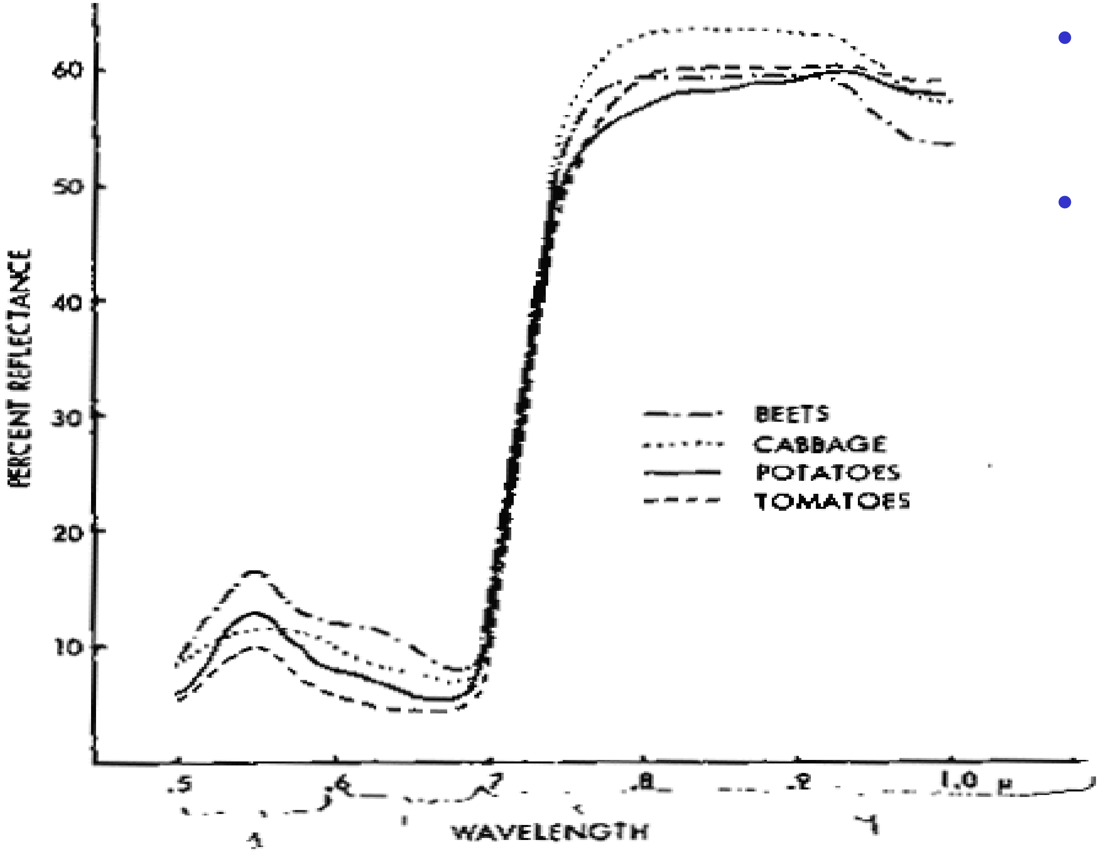


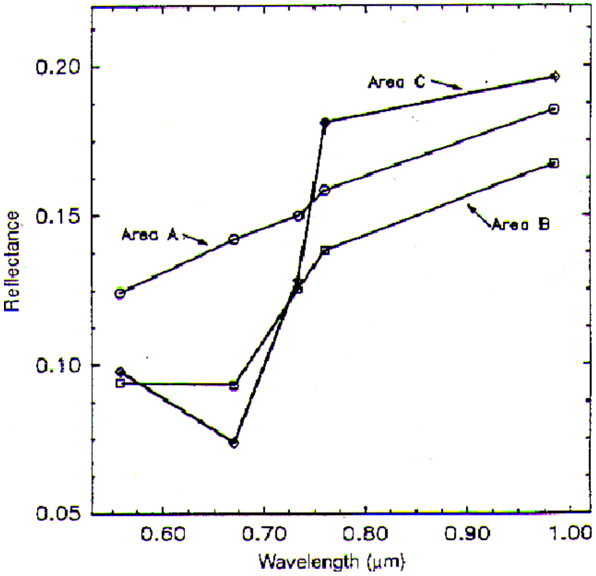
Daily Light Curves for Earth with No Clouds



Optical Plant Signature as a Biomarker

- Chlorophyll causes strong absorption blue-ward of 0.7 µm
- The high reflectance red-ward of 0.7 µm is from light scattering in the air gaps between plant cells
- Photosynthetic plants have a spectral signature when viewing Earth, even if Earth is not completely covered with plants





Confusion and Impacts for Architecture Families

- “Confusion" means the instrument cannot properly distinguish individual sources because it lacks spatial resolution, whereas "interlopers" are properly imaged, but cannot be classified without further information.
- Confusion noise is proportional to the strength of the confusing sources, while background noise is proportional to the square root
- Background noise can be reduced by longer integration, but confusion noise cannot
- Artifacts originate from the poor sampling of the (u,v) plane. These can be largely removed by non-linear image restoration processing with deconvolution algorithms such as CLEAN
- As a class, filled-aperture systems will perform better than dilute-aperture systems at the same angular resolution in discovering and characterizing exoplanets in the presence of confusion sources
- For dilute-aperture systems to approach the performance of the filled-aperture system, the cost is a large increase in the overhead of time used to reconfigure the telescopes

Astronomical Sources of Confusion

- Stellar sources are unlikely to be significant sources of confusion for either an optical or MIR TPF mission
- High-redshift galaxies are a potential source of confusion for MIR TPF
  - While the Hubble Deep Field observations do not reveal any new populations of galaxies at 29th magnitude that will limit planet searches, there is little known about the MIR universe at faint magnitudes.
  - Extrapolation from existing data is dangerous as there is likely a new population of high z sources: stars in galactic spheroids (bulges and ellipticals) likely formed at $z > 3$. If they formed at $z = 5$-10, then they may be a significant source of confusion for a mid-IR TPF
  - In plausible cosmological models, faint sources (~ 0.1 μJy) can account for most of the mid-IR background. (Haiman et al. 2000).
    - (1) There could be up to 1 false detection per 10 pointings,
    - (2) The 3-sigma limit can be just around the flux threshold of interest, 0.1 μJy.
- Structure in the zodiacal light is a particularly dangerous source of confusion as it will be in all observations of the system

Can We Mitigate Confusion?

- Since planetary systems rapidly move relative to galactic backgrounds, repeated observations can eliminate the effects of confusion from those backgrounds
  - They are unlikely to be a “showstoppers” for either optical or MIR missions
  - They may potentially increase observing time needed for MIR missions
- Interferometers require multiple observations at different spacing to construct an image and identify structures
  - Detailed simulations will be needed to evaluate the sensitivity of interferometers to substructure in the exozodi disk

#2 Science Rationale – Astrophysics with TPF

- For astrophysics, better science performance means:
  - More opportunities for 'astrophysics' instrumentation
  - More observations possible
  - Wider community served by unique capabilities
- Criterion #2: Richness of astrophysical science opportunities
  - Superiority of general-use over niche capability
  - Superiority of accommodating general-use focal-plane instrumentation

MIR TPF: Science Goals

- Cosmology:

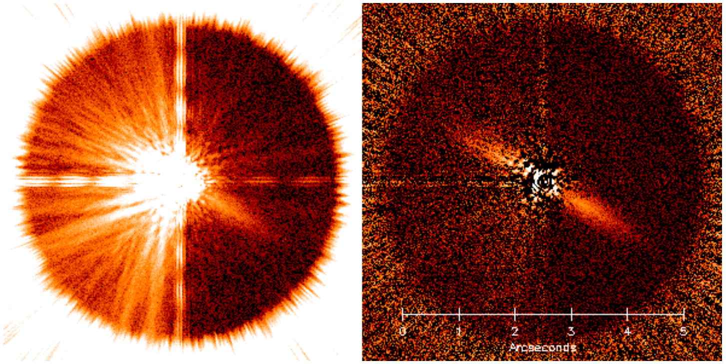
  How do galaxies form? Probing the high-z universe. The combination TPF / NGST could reach to $z = 15$, although the number of images from TPF will be limited. Improved resolution by TPF will elucidate the nature of the new objects detected by NGST

- Protostellar environments:

  How do planets form? By imaging the protostellar disk, we can complement the planet detection program

- QSO host Galaxies:

  How do black holes affect their environment? Many galactic nuclei are dust enshrouded. Mid-IR observations will enable us to image the heart of the beast



Circumstellar Disk

Astrophysics with an Optical TPF

- Hubble Space Telescope has been the dominant astronomical instrument of the past decade. It has produced major advances in fields ranging from planetary astrophysics to cosmology

- Optical TPF is the natural successor to Hubble Space Telescope
  A. Resolution 4 x HST
  B. Collecting Area 10 x HST
  C. Sensitivity for many spectroscopic observations 100 x HST
  D. Would have broad support in optical/UV community

- Environment is an operational NGST and post-HST
  - Although potential benefits of simultaneous Hubble and NGST operations are clear, those are now a fading possibility due to further slips in NGST
  - Because NGST could do better than TPF on many astrophysics problems, that makes a MIR TPF less appealing from the criterion #2 point-of-view
  - Optical TPF's UV capability is unique
  - An optical TPF will simplify NGST by relieving pressure for 0.5 – 1 micron capability

Unique Astrophysics Capabilities for an Optical TPF

- UV capabilities (SUVO program)
- Optical coronagraphy
- High resolution optical studies
  - Achieving 20 milliarcsecond ground based imaging on faint sources will require revolutionary advances in adaptive optics
- Large focal plane will enable parallel observations. During every planetary characterization, we can make a much deeper version of HDF!
  - Because optical planet observing is more efficient for TPF, it also frees up more time for subsequent astrophysics

HST's striking optical images have not only had a profound impact on the scientific community but also on the general public. (Very few VLA maps are as striking as the Hubble legacy images. Mid-IR TPF's u-v plane coverage will be vastly inferior to VLA.)

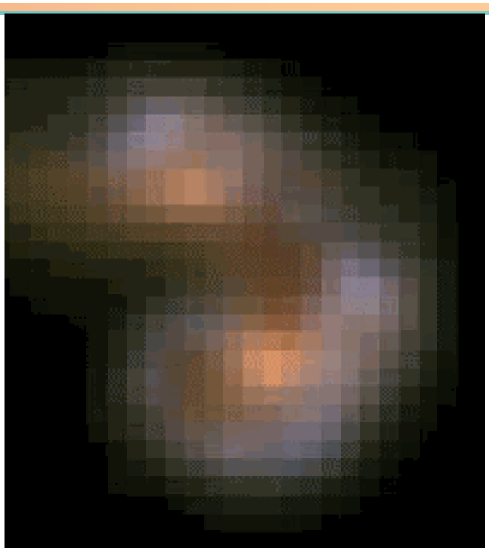
Tracing the Cosmic Web – UV/Optical Science with TPF

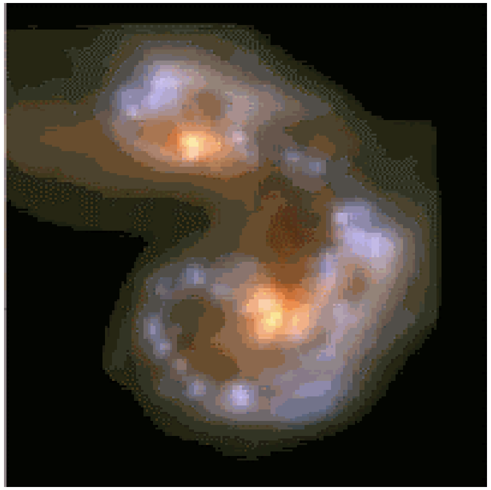
- White Paper of the UV-Optical Working Group (UVOWG)
  - J. Michael Shull, Blair D. Savage, Jon A. Morse, Susan G. Neff, John T. Clarke, Tim Heckman, Anne L. Kinney, Edward B. Jenkins, Andrea K. Dupree, Stefi A. Baum, and Hashima Hasan
- HST 10X study
  - H. Ford, J.R.P. Angel, C.J. Burrows, J.A. Morse, J.T. Trauger, D.A. Dufford

- Key unanswered questions include:
  - Where is the rest of the unseen universe?
  - What is the interplay of the dark and luminous universe?
  - Where are the baryons?
  - How did the IGM collapse to form the galaxies and clusters?
  - When were galaxies, clusters, and stellar populations assembled into their current form?
  - What is the history of star formation and chemical evolution?
  - Are massive black holes a natural part of most galaxies?
- A large-aperture UV/O telescope in space will provide a major facility for solving these scientific problems. Optical TPF will have many of the capabilities of the “Class II” UV mission proposed by UVOWG as the major goal for the field in the next decade.

Extending our Vision of the Nearby Universe

- When did stars form? HST has revealed complicated star formation histories in the nearest dwarf galaxies. Optical TPF would extend our vision to beyond the Local Group: Centaurus A, M81, M101, and their complement of dwarf companions. The Horizontal Branch (HB) could be viewed out to the distance of the Virgo Cluster, and the Red-giant Branch Tip (TRGB) could be detected at the Coma Cluster distance.
- How were galaxies formed? HST has shown intriguing hints that galaxy morphology evolves. Why are few barred galaxies at z > 0.5 ?
- How were black holes formed? HST has detected black holes in ~30 nearby galaxies. Optical TPF would be able to increase the sample to more than 1000 nearby galaxies.
- How old is the universe? Optical TPF would be capable of detecting white-dwarf sequence in globular clusters. This would provide an independent stellar evolutionary estimate of the age of the universe.
- What is the relationship between black holes and their hosts? With TPF's coronagraphic capabilities, it will be particularly powerful instrument for studying the environment around black holes.
- What are the building blocks of galaxies? A vigorous study of High-velocity Cloud (HVC) phenomena will require a spectroscopic facility more capable by at least a factor of ten than COS.

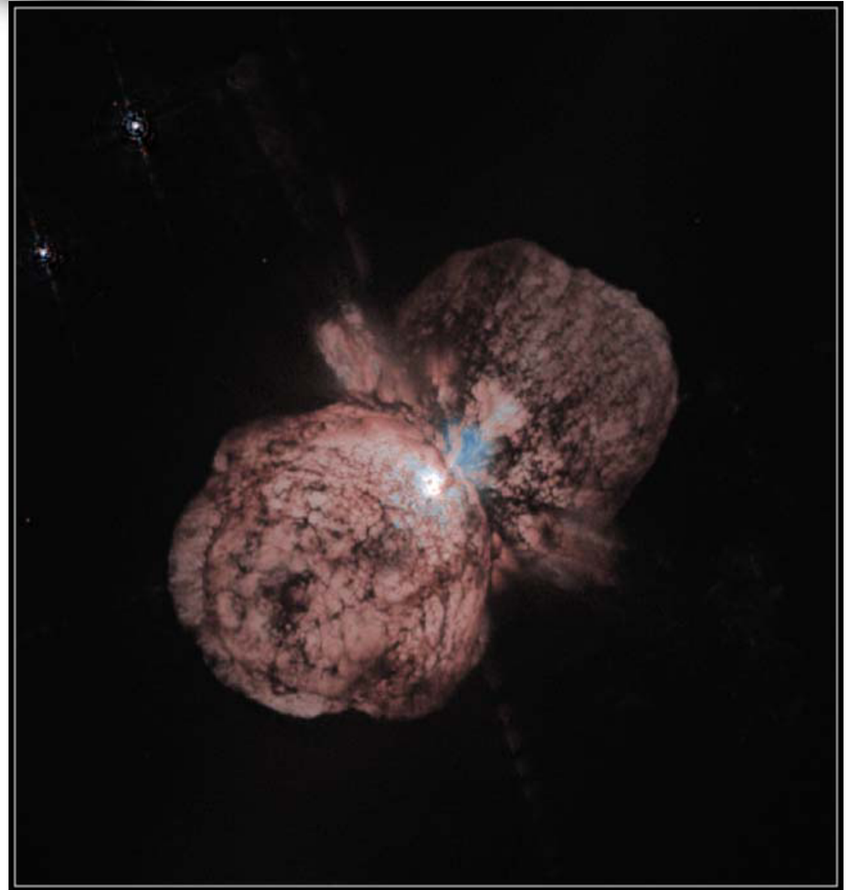




Studying the Dark Energy and Dark Matter

- Perhaps the two greatest mysteries in astrophysics are the nature of the dark energy that is driving the acceleration of the universe, and the composition of the dark matter that makes up most of the mass in galaxies.
- These two components make up 97% of the mass of the universe!
- Optical TPF will yield insights into these problems:
  - By detecting Cepheids out beyond Coma, we can measure H_o to 1% accuracy. When combined with MAP's measurement of the distance to the surface of last scatter, this yields an accurate measurement of the equation of state of the universe.
  - By measuring surface brightness fluctuations out beyond the Coma cluster, it will be able to trace the large scale distribution of matter.
  - With wide-field capability, optical TPF will be able to trace the distribution of dark matter as a function of redshift through gravitational lensing. The evolution of the mass power-spectrum is one of the most sensitive astronomical probes of the nature of the dark matter and dark energy.
  - With detailed studies of high redshift supernova, it will be able to deepen our understanding of these important "standard candles".

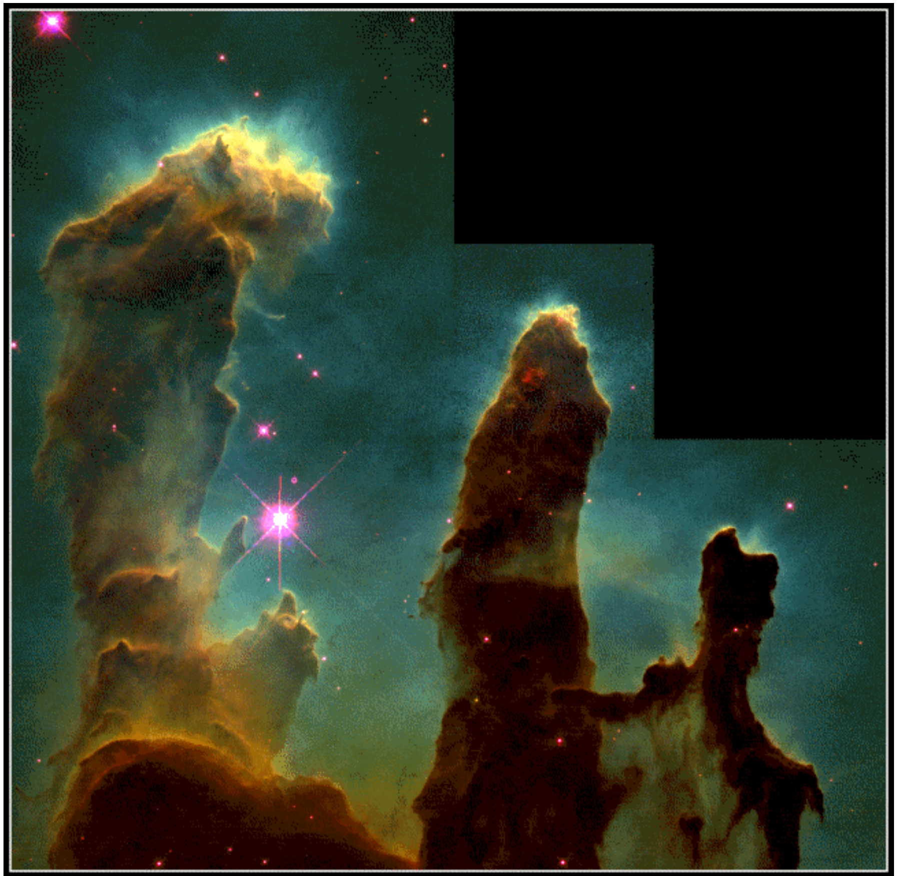
Imagine These Images at Much Higher Resolution! (or with a Sparse Aperture?)



Eta Carinae HST • WFPC2

PRC96-23a • ST Scl OPO • June 10, 1996

J. Morse (U. CO), K. Davidson, (U. MN), NASA

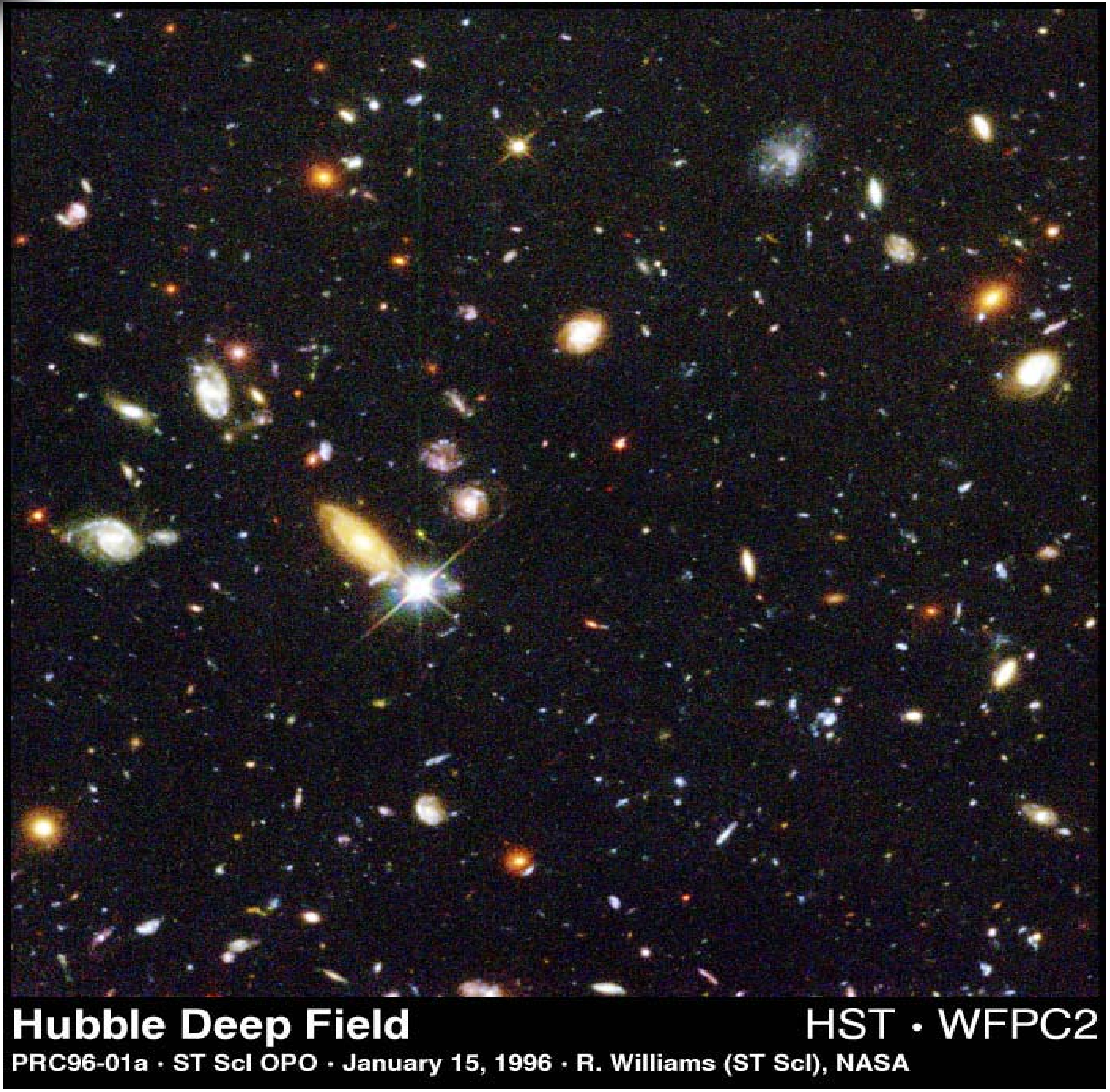


Gaseous Pillars • M16 HST • WFPC2

PRC95-44a • ST Scl OPO • November 2, 1995

J. Hester and P. Scowen (AZ State Univ.), NASA

Optical TPF: Images Galaxies 3 Magnitudes Fainter than and with 4x the Resolution of HDF



And this can be done easily in parallel mode, while collecting planet data!

ORIGINS Science with TPF – Details (1)

- **How common are planets and what is the likely diversity of planetary systems?**
    - Most stars form in OB associations (NOT in quiescent dark clouds!) where radiation fields and winds rapidly erode disks and planetary systems like ours may be relatively rare
    - Rocky planets might form in Orion-like environs from solids that can resist photo-ablation, but such planetary systems are likely to lack giant planets rich in H and He unless such planets form prior to irradiation by disk gravitational instability
    - A visual TPF can access disks striped clean of their host clouds (e.g., Orion's proplyds); the IR TPF is better suited for studying embedded objects
- **What is the chemical and physical makeup of disks?**
    - Spectro-imaging in the IR molecular line such as CO, ice bands such as CO^2 and H^2O, and solid state features such as those due to silicates and organics can be used to diagnose grain size distribution and composition and the evolution of these properties with stellar age and environment
- **When do macroscopic proto-planetary bodies first appear in disks?**
    - Search for thermal emission from warm protoplanets heated by impacts, disk gaps produced by planetary sweeping, induced spiral density waves, and debris clouds produced by proto-planetary collisions. An optical TPF can probe the properties of proplyds and disks seen in silhouette.
- **How do accretion disks evolve into debris disks and exo-Zodi clouds?**
    - Probe circumstellar gas and dust surrounding young and moderate-age stars. Sample populations with ages ranging from 10 to > 1,000 Myr exist within 200 pc of the Sun

ORIGINS Science with TPF – Details (2)

- **What processes determine the stellar initial mass function (IMF)?**
  - Coronagraphy can search for faint dwarf stars near bright high mass ones. Do the low mass cutoffs of the IMF vary with cluster size and environment? To what extent do dynamical interactions determine stellar masses by shifting protostars out of their accretion zones? How frequently do violent proto-stellar dynamical interactions abort planetary system formation?
- **How do high mass stars and rich clusters form?**
  - By direct accretion or by cannibalizing lower mass protostars? The IR TPF is uniquely suited to probe the highly obscured (A_V > 100 mag) and highly clustered (> 10^5 stars/cubic pc) environs in which high mass stars appear to form. Source complexity would dictate that an IR array with many small elements would perform better than one with a few large elements
- **How does star formation occur in the Galactic center?**
  - The IRS 16 cluster in the inner few parsecs of our Galaxy apparently formed within a few pc of a 10^6 Solar mass black hole. How do stars form in such violent and strongly shearing environments? Galactic Center studies with an IR TPF may shed light on nuclear star bursts in galaxies, the formation, fueling, and evolution of black holes in galactic nuclei, and the ignition of the QSO and AGN phenomena.
- **Gravitational lensing towards the GC as a planetary search method**
  - IR TPF studies towards the Galactic center might also resolve the background confusion in future IR gravitational lensing events and provide an independent statistical method for determining the mass spectrum and frequency of extra-Solar planets down to an Earth mass

Other Prospects for Coronagraphic or Interferometric TPF Astrophysics

- With a formation-flying MIR Interferometer:
  - Each element could also operate as 4 independent HSTs for optical/UV
    - High resolution optical studies
- A visible-light TPF coronagraph offers other possibilities:
  - Adding a pair of small satellites (small telescope and a beam combiner) could make a two element optical interferometer with a baseline of a few km
    - The combined system would have a resolution in the near-UV to image a black hole in M87 or NGC 4649. These black holes masses of ~2E9 solar masses at distances of ~16 Mpc mean that the system could resolve the Schwarzschild radius
  - If the optical TPF was set up so that it could be converted into an element in this interferometer, then the larger system could be launched later
  - The two element optical interferometer could then be seen as a test-bed for an optical Planet Imager

G: Implementation Analyses

Noecker, Kasdin, Crocker, Epstein, Kilston

Technology (including Orbits)
Cost
Risk
Robustness and Reliability
Heritage Path toward Future Missions

#3 New Technology Requirement Differences – by Family

Technology Element	Emitted-Light	Reflected-Light
Opto-Mech. Technologies		
Large-aperture monolith	n/a	Needed (NGST +)
Super-polished mirror	n/a	Needed (Eclipse . . .)
Active optics control	n/a	Needed (Eclipse . . .)
Masking/nulling	Needed (Achromatic)	Needed (Low Leakage)
Optical path control	Needed (Cryo)	n/a
Rad-hard MIR detectors	Needed	n/a
Spacecraft Technologies		
Formation control	Needed (autonomous FF)	n/a
Advanced propulsion	Needed	n/a
Cryo-thermal control	Needed (w/Formation)	n/a
Contamination control	Needed (w/Formation)	May be important

Green = Advantage, Red = Disadvantage

New Technology Requirements-Orbits

- Orbit and Maneuver Topics
  - Alternate Orbits: LEO Orbit, Out-of-Ecliptic Orbit; Launcher implications
  - Interferometer Configuration and Propulsion Trade Study
  - Formation-Keeping and Propulsion Study
- LEO Orbit only feasible for Visible/NIR system, thermal issues are minor
  - 6am/6pm Sun-synch. orbit: no thermal snap; low-cost, low-rad, serviceable
  - Very limited capability to do long integration times over large parts of sky
- Thermal requirements of IR observatories require non-Earth centered orbits
  - L2 halo orbits; Earth-trailing, drift-away orbits (heliocentric)
  - Both of these trajectories suffer from noise due to the local Zodiacal cloud in the ecliptic made up of interplanetary dust (IPD)
- Out-of-Ecliptic Orbits can reduce noise due to Zodiacal cloud
  - Stochastic, structured search for initial conditions uses genetic algorithms (GAs) to maximize the normal excursion for a given launch vehicle energy
  - Three families of orbit trajectories were identified and characterized
    - Two optimal trajectories were found, a low-energy and a high-energy orbit

Potential Benefits with Normal Displacements of Several Tenths of AUs

Mirror size and mass reduction

Reduced development and manufacturing costs

Shorter integration times

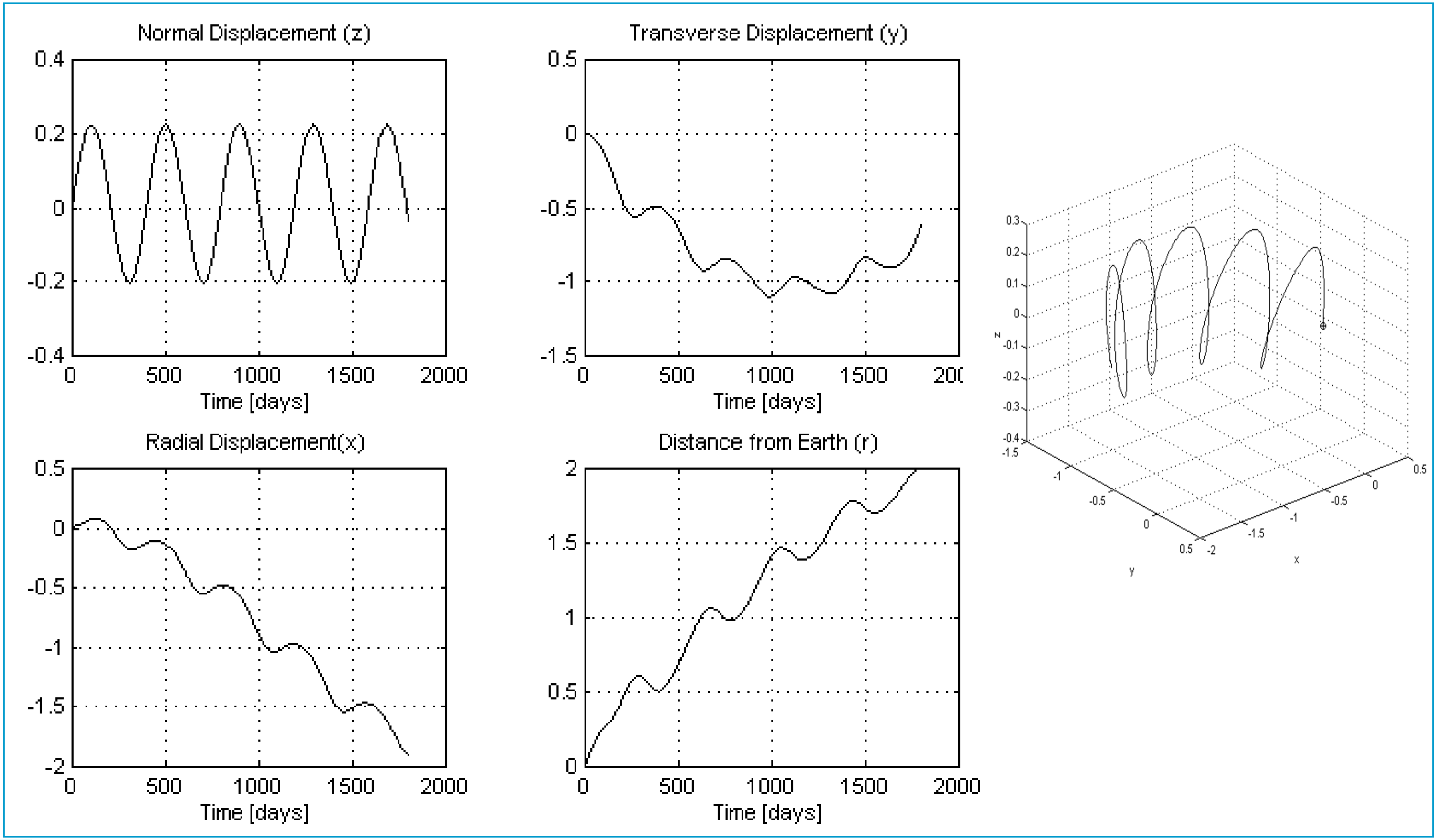
More observations for a given lifetime

Reduced risk of micrometeorite damage

Smaller shields and extended mission lifetime

- Increased cost-effectiveness
- Enables future missions
- Better scientific return

Low-Energy Optimal Trajectory

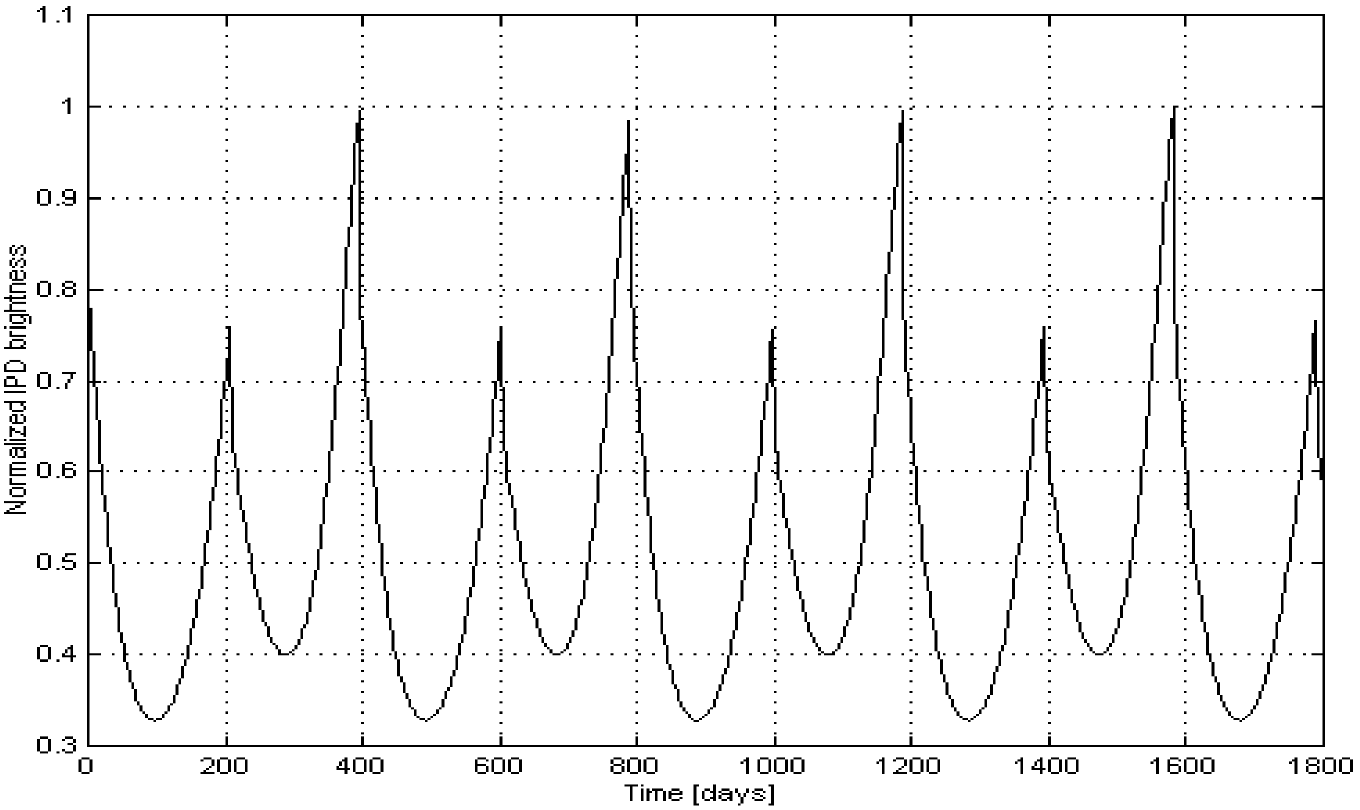


Low-energy Orbit Reduces Zodi Brightness by More Than 50% During 60% of Mission

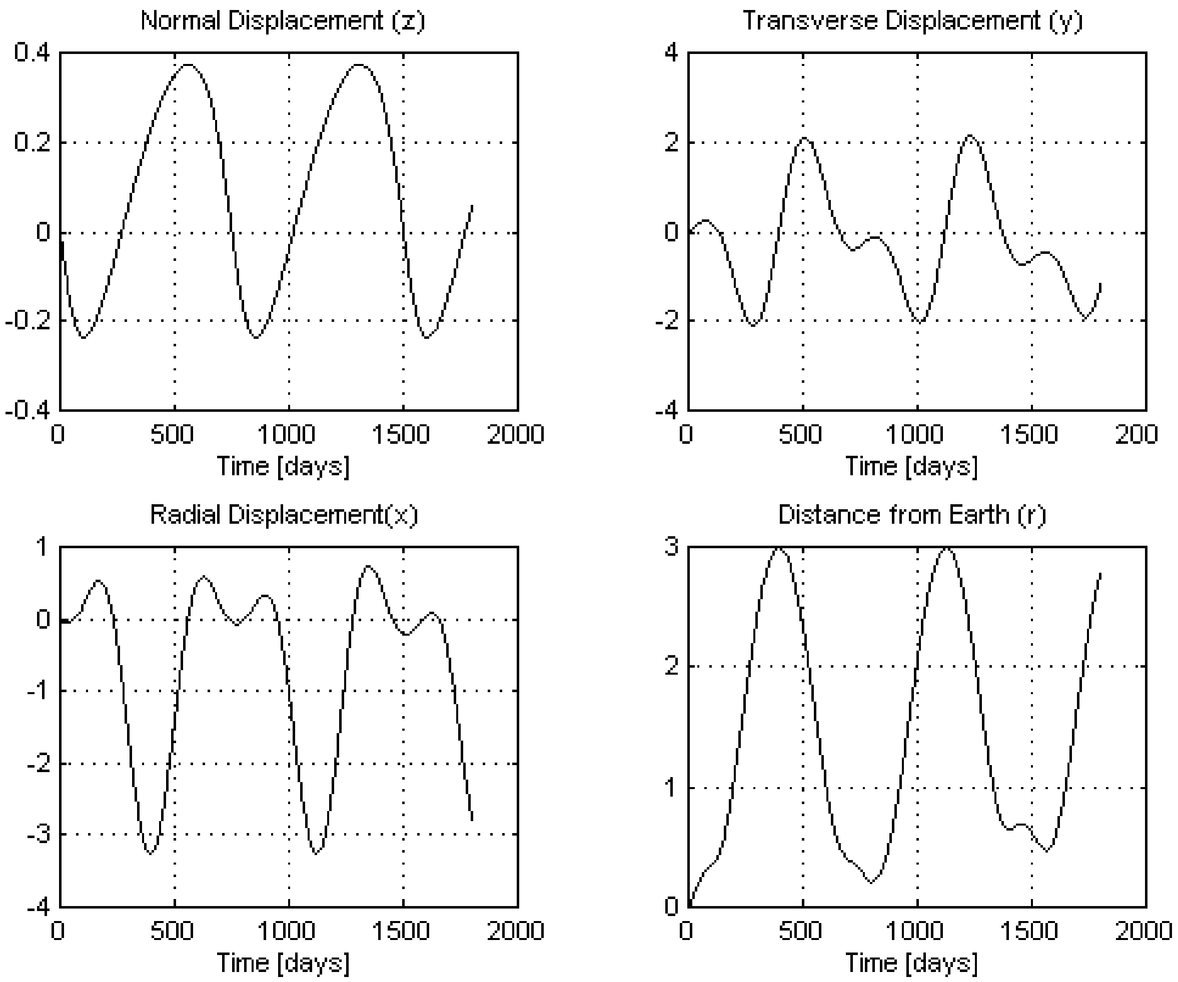
Maximum reduction: 67%
Mean reduction: 45%

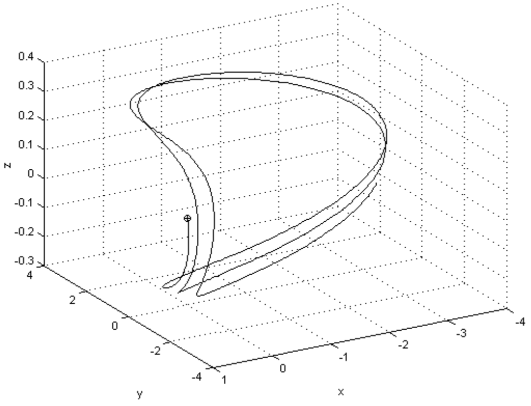
→

Mirror diameter reduction: 20%
Maximum mass reduction: 35%



High-energy Optimal Trajectory





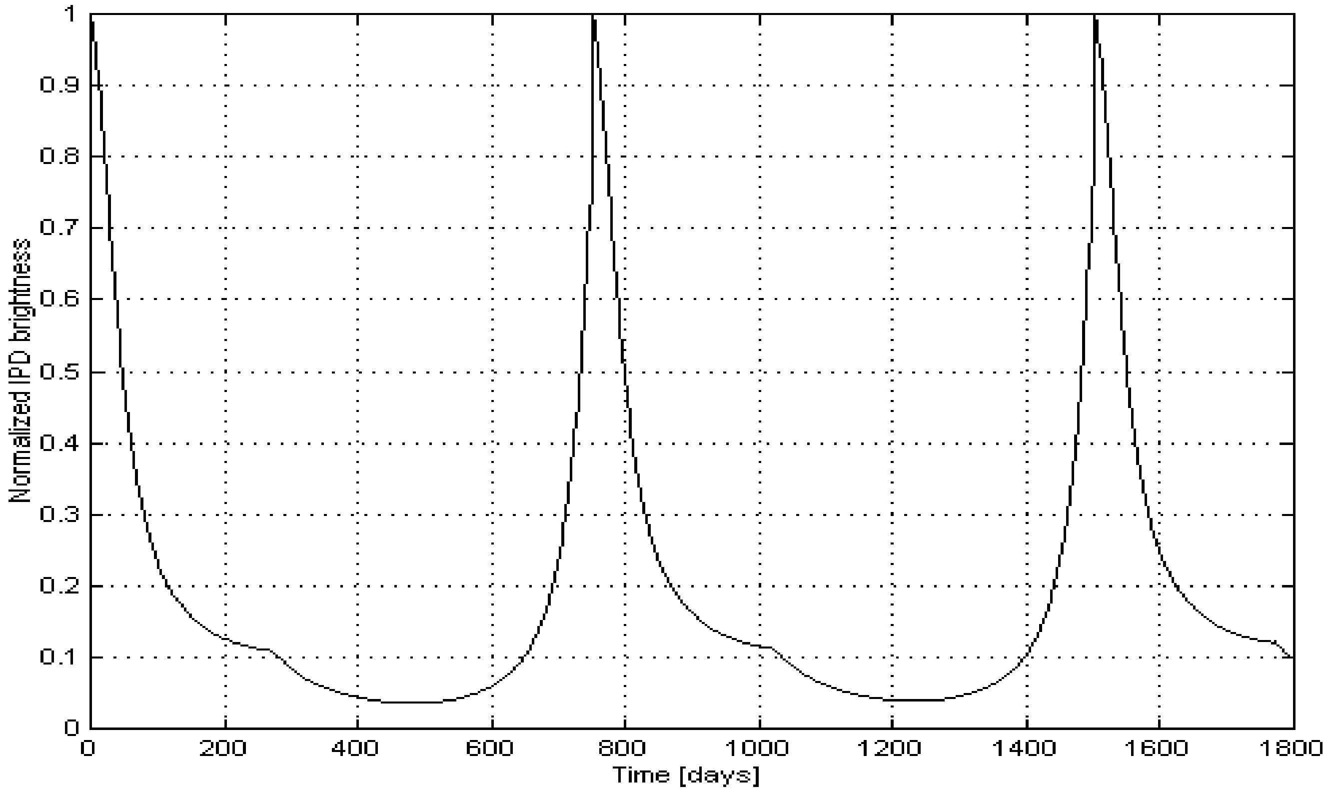
Orbit with closest approach to Earth of 0.2 AU

High-energy Orbit Reduces Zodi Brightness by More Than 70% During 82% of Mission

Maximum reduction: 97%
Mean reduction: 75%

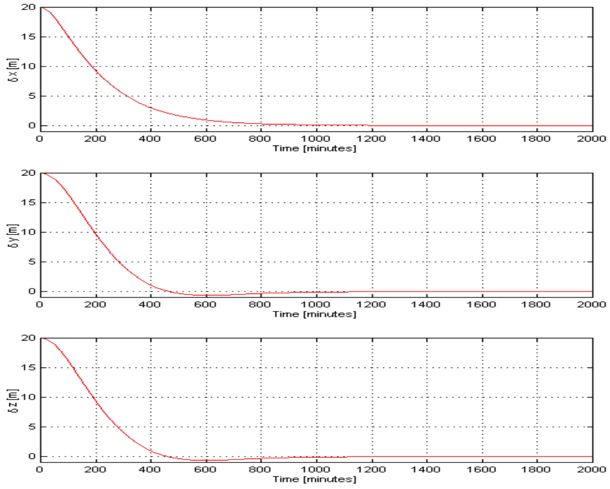
→

Mirror diameter reduction: 30%
Maximum mass reduction: 50%

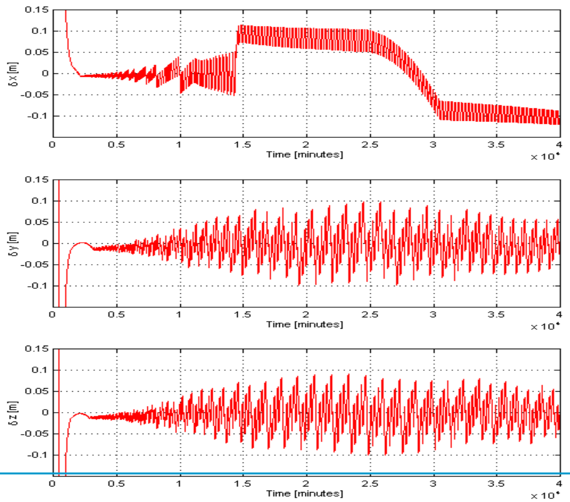


Formation Flying

- For optimal formation control on the out-of-ecliptic trajectories
  - Each vehicle is controlled to its own pre-designed reference trajectory
  - Spacecraft relative positions are controlled. FF needs thrust up to 5 mN
- The first approach decouples the control problem - each vehicle optimal control is independent of the other vehicles' states and controls
- Conclusions have major bearing on propulsion system design and selection
  - The maximum thrust limit constrains the control bandwidth
  - The minimum thrust limit determines the formation keeping accuracy



Zooming in:



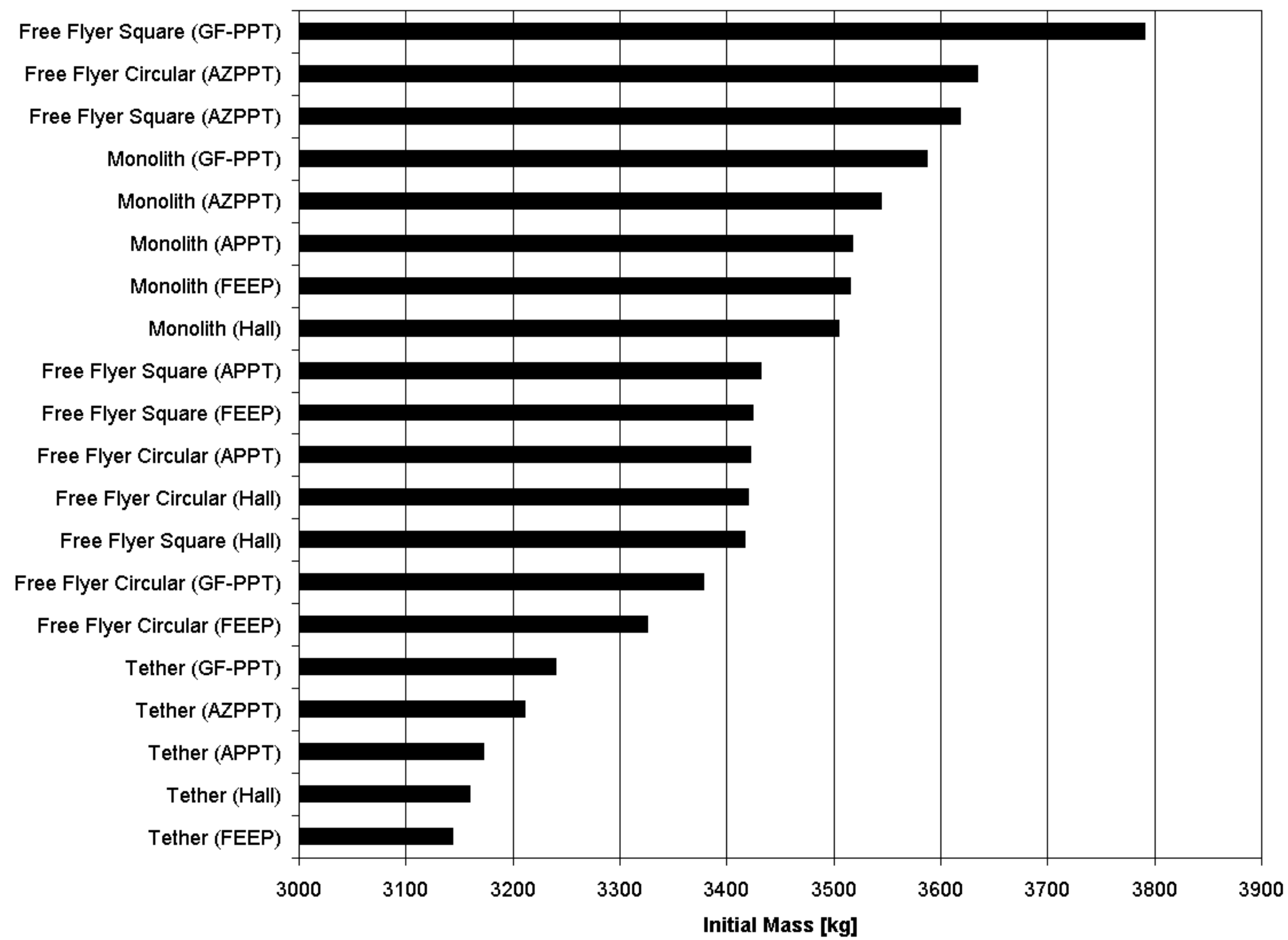
A limit cycle evolves due to minimum thrust limit

To obtain a ±1 cm accuracy, minimum thrust needs to be at least 1 μN

Propulsion Requirements Study

- Free-flying system demands advanced propulsion systems
    - Requirements include thrust efficiency and low contamination by propellants
- Assumptions
    - Analyzed worst-case scenario of planet finding (8-hour observation period)
    - Considered rotation and pointing of formation (mN propulsion) only. Did not consider mN propulsion chores (e.g., sub-cm formation keeping)
    - Used mass and power reqts. (excluding propulsion) from NASA TPF study
- Propulsion options: Hall thrusters, FEEP, Ablative PPTs, z-pinch APPTs and Gas-fed PPTs
- Configurations studied: free flyer, monolith and tether
    - Eliminated duplicate subsystems on the structurally connected configurations for mass reductions
- Methodology
    - Determined propellant mass/power requirements for mission
    - Determined mass of the power supply (solar panels, batteries, etc.)
    - ITERATED until total mass and power requirements converge

Results – Total Initial Mass (Entire System) by Architecture-Thruster Combination



Propulsion Conclusions

- Depending on architecture and propulsion type, total initial masses ranged between 3100 and 3800 kg
- In general, the order of total initial mass by architecture is
  - Tether (lowest initial mass)
  - Free-flyer (mid-range initial mass)
  - Monolith (highest initial mass, but only around 100 kg more than the free-flyer)
- Plasma propulsion offers substantial mass savings over chemical
- Any of the five types of plasma thrusters considered will do: The corresponding total spacecraft masses are all within 15% of each other.
- The two main differentiating indices between propulsion options are
  1) Their technology readiness
     - Decreasing order: Hall, PPTs, FEEP
  2) Their potential for spacecraft contamination by exhaust plume products.
     - Decreasing order: FEEP (cesium), Ablative PPT (Teflon), Hall (xenon, Krypton), GF-PPT (all inert gases)
- No option covers full dynamic range required by formation keeping

New Technology Requirements – Interferometer (1)

- As discussed in the propulsion section, for free-flyers mission-throughput versus expendables may be a significant issue
- Nulling Stability (Norm Jarosik)
  - TPF book established a null depth requirement based on a statistical noise contribution from the leakage of stellar photon noise of less than 25% of the noise budget. This led to a phase error requirement of 3 nm
  - This analysis neglected the systematic error due to the mean stellar leakage. A 3-picometer drift away from null could result in a leakage of the mean intensity equal to the planet. This can lead to a 3-picometer stability requirement on the phase error. Further analysis of the implications is needed
- Null Locking/Pointing Control (Dick Miles)
  - Unclear how system stays locked onto null once proper delay line is established. (On the ground this control is typically accomplished via dithering.)
  - What makes system stay locked at the null with no signal to control the feedback system. A dithering approach might be used where data only taken when star passes through null, keeping each telescope within 1/1000 of Airy peak

New Technology Requirements – Interferometer (2)

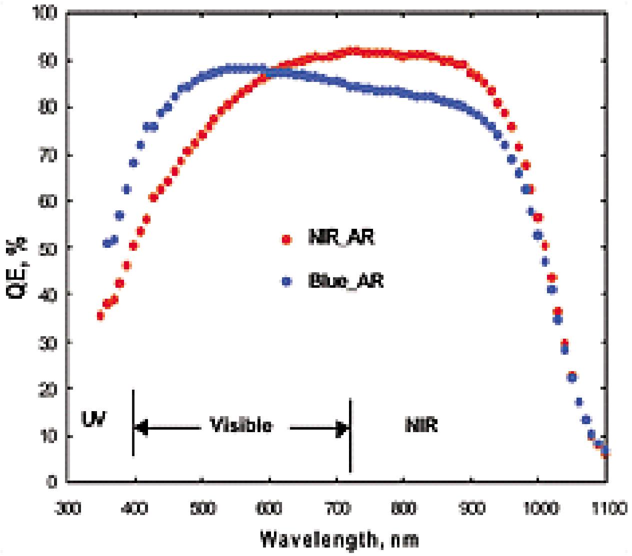
- Cryo-mechanisms (especially delay-line control)
- Polychromatic analysis and simultaneous phasing for dispersed channels
- Spatial filter optimized across wide-passband MIR
- Extremely accurate automatic fringe detection, tracking, and position control
- Polarization control
- Low-aberration and low-dispersion beam combiners and beam splitters
- MIR detectors and readouts with extremely low, dark current
  - HgCdTe PC Detectors, Spectral coverage 6.12-17.76 μm, Op. Temp. 65 K
  - Up to order of magnitude improved performance in next 10 years
- Signal amplitude control and matching, in light of aging of optics and coatings, contamination, degradation, etc.
- Cryocooling

New Technology Requirements – Coronagraph

- SiC for large monolith ?? Low-scatter surfaces
  - One large mirror may be bigger technology challenge than several small ones (that may be true for the optics, but not necessarily for the system)

- Pixels ~ 10 mas; to cover 3pc, 15 au orbits, need a 1024 x 1024 array
  - 0.4 - 1.0 μm and 0.9 - 2.5 μm arrays
    - Available in that size

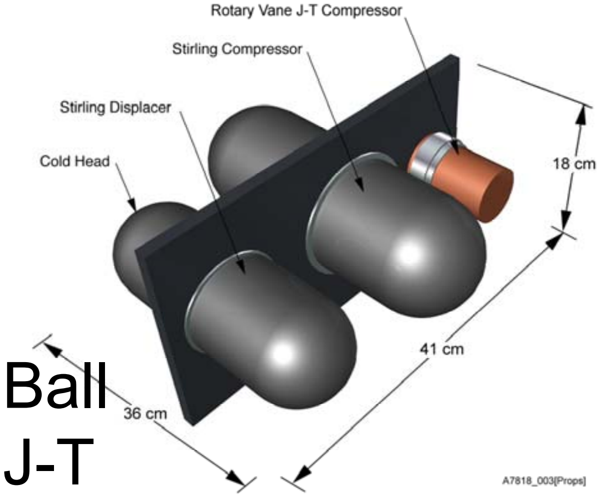
- Rockwell's New Hybrid Visible Silicon Imager
  - CMOS alternative to CCDs
  - ~100% optical fill-factor; high, wide-l QE
  - Non-blooming; Low Dark Current
  - High Inherent Radiation Hardness



New Technology Requirements – Thermal/Cryogenics

- Cryo Cooler for MIR TPF (leverage from or joint with NGST)
  - Leading cooler candidates (all need further development)
    - Ball J-T, Creare Brayton, and JPL J-T
  - 6 K cooler requirements similar to NGST MIR requirements
    - Temperature, load, lifetime, etc.
    - But, NGST MIR is an option, while 6 K may be required for TPF
  - If NGST doesn't commit to MIR or 6 K cooler, then TPF needs to pick it up
  - Unique to TPF
    - potentially greater vibration sensitivity than NGST
- Sun Shields (leverage off NGST with new design)
  - Can leverage off NGST, but need design and maybe technology efforts to respond to unique TPF needs
  - Unique to TPF
    - Interaction/views with other vehicles in formation
      - Light scatter
      - Thermal radiation
    - Greater material contamination sensitivity

Creare Brayton



Ball J-T

#4 Life-cycle Cost

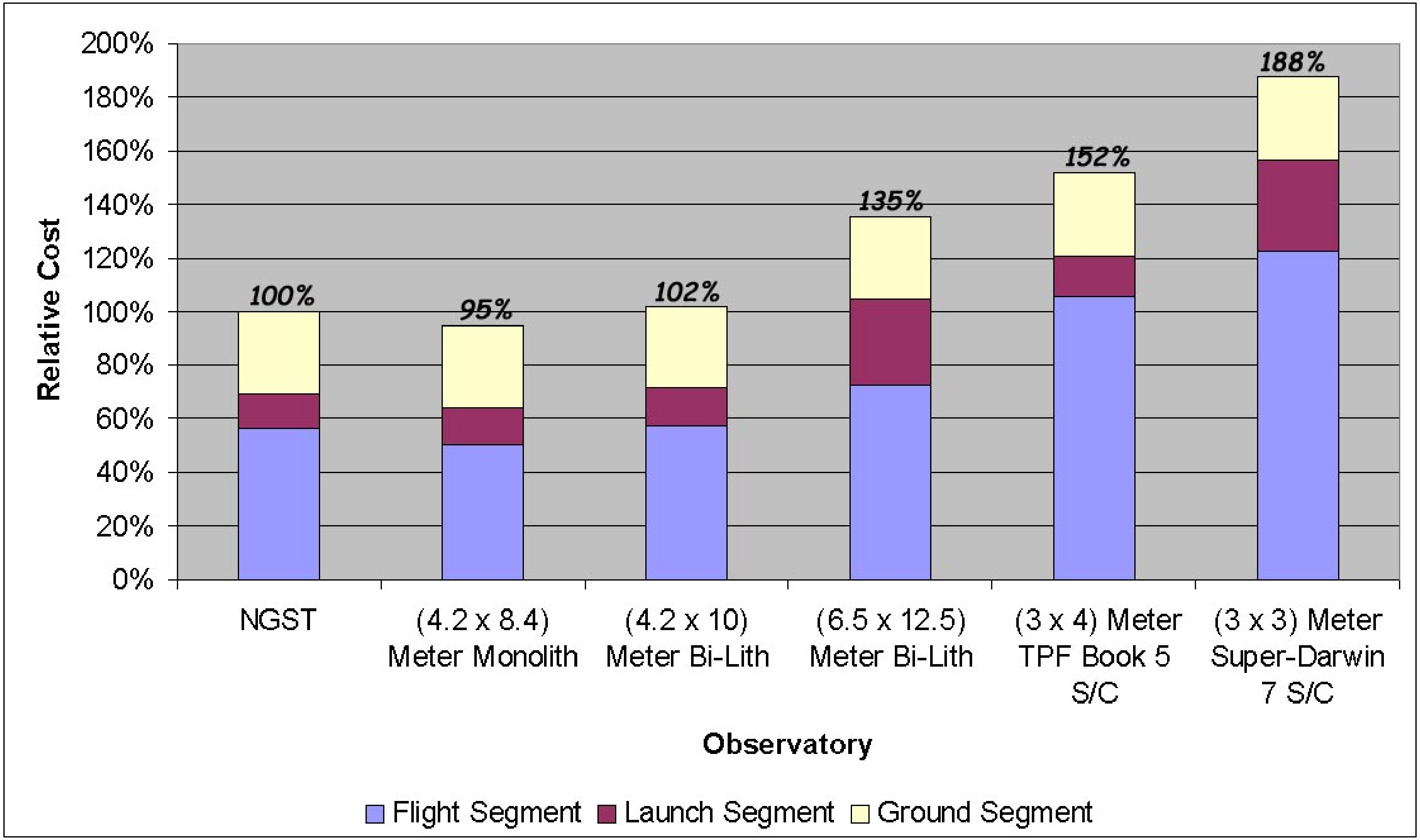
Cost Factor	**Emitted-Light**	**Reflected-Light**
Space Element		
Instrument	IR/cryo Beams, OPD, nulling	One-telescope cheaper Less tech. development
Spacecraft Bus	Many	One
Integ. and Test (system-level)	(Cryo/multiple testing)	Less integ. and test
Launch Vehicle	Atlas V/Delta IV	Atlas V/Delta IV
Ground Element		
Infrastructure	More processing power	
Operations	More complex maneuvers	
Science Efficiency		Lower cost per planet

Green = Advantage, Red = Disadvantage

TPF Architecture Cost Comparison Matrix

		Coronagraph			Formation Flyers	
Cost Element Description	**NGST**	**(4.2 x 8.4) Meter Monolith**	**(4.2 x 10) Meter Bi-Lith**	**(6.5 x 12.5) Meter Bi-Lith**	**(3 x 4) Meter TPF Book 5 S/C**	**(3 x 3) Meter Super-Darwin 7 S/C**
Total Telescope Collecting Area (M^2)	50.2	27.7	33.0	63.8	37.7	42.4
Flight Segment						
Project Management		0.4%	0.4%	0.4%	0.5%	0.6%
Integration & Test (I&T)		0.6%	0.7%	0.8%	0.9%	0.9%
Systems Engineering		4.1%	4.1%	4.1%	4.9%	5.7%
Spacecraft (Bus)		6.1%	11.1%	11.1%	38.8%	44.3%
Optical Telescope Assy		12.8%	15.2%	29.4%	19.2%	21.6%
Instrument Elements		16.5%	16.5%	16.5%	27.5%	34.4%
Mission Operations Development		2.6%	2.6%	2.6%	3.1%	3.6%
Contingency		7.0%	7.0%	7.7%	10.6%	11.3%
Subtotal		50.1%	57.7%	72.7%	105.4%	122.4%
Launch Segment						
Launch Vehicle		12.2%	12.2%	27.8%	13.3%	30.0%
Contingency		1.7%	1.7%	4.2%	2.0%	4.2%
Subtotal		13.9%	13.9%	32.0%	15.4%	34.2%
Ground Segment (10 Yrs)						
Science Operations		27.8%	27.8%	27.8%	27.8%	27.8%
Spacecraft Support Operations		2.8%	2.8%	2.8%	3.3%	3.3%
Subtotal		30.6%	30.6%	30.6%	31.1%	31.1%
Total	**100.0%**	**94.6%**	**102.2%**	**135.3%**	**151.9%**	**187.7%**

TPF Architecture Cost Comparison



Science Throughput – Cost per HZ Planet Measured (Example Estimate)

- This could be the ultimate measure of TPF system cost-effectiveness
- Evaluation depends on estimation of:
  - System cost over lifetime
  - Number of stars searched for planet over system life
  - Number of habitable planets per star searched

	Spergel Coronagraph	Darwin Interferometer
System cost over lifetime	$1B	$2B
Stars searched during life	200	100
Habitable planets per star	0.3	0.3
Cost per HZ Planet	$17 M	$67 M

#5 Risk Assessment

Risk Factor	**Emitted-Light**	**Reflected-Light**
Cost	Beam and contamination control, cryo	One-telescope cheaper
Technology	Technology program now in place	Less technology development
Adequate testing	Separated instruments	Easier to test
Schedule	Multiple instruments	Large monolith mirror
On-orbit failures	Contamination levels	Easier to service

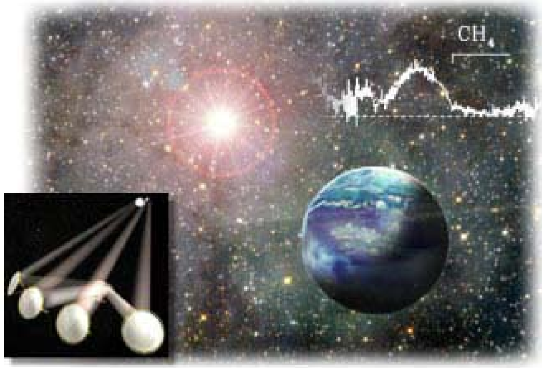
Green = Advantage, Red = Disadvantage

#6 Reliability and Robustness

Reliability/Robustness	Emitted-Light	Reflected-Light
Reliability Factors		
Single-point failures	Multiple spacecraft	Adaptive optics
Redundancies		Multiple detector types
System reliability		Fewer components
Robustness Factors		
Number of targets in 5 years		Higher collection rate
Variety of target geometries	Closer star IWDs	Greater OWDs
	Can fit to astrophysics	Greater sky coverage
Resilience to larger exozodi		Greater exozodi margin
Resilience to high confusion	Interf. easily confused	Less confusion in visible
		Imager deals with confusion

Green = Advantage, Red = Disadvantage

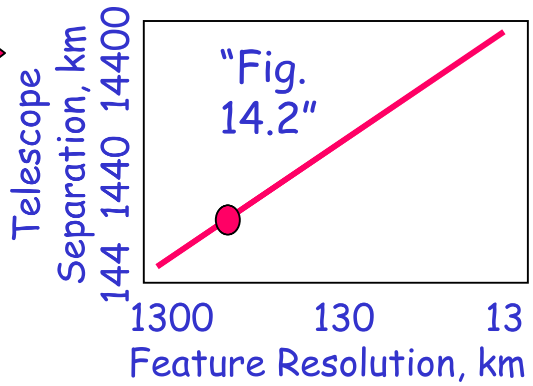
#7 Heritage Path to Future Planet Detection/Characterization Missions

Mission Technologies	**Emitted-Light**	**Reflected-Light**	
Life Finder			
— High-SNR spectroscopy			
Visible wavelength coverage		√	
MIR wavelength coverage	√		
Large apertures (25 m)		√	
Nulling	√	√	
Planet Imager			
— Super-high resolution			
Large baseline IF with FF	√		
Visible wavelength coverage		√	
Large apertures (40 m)		√	
Nulling	√	√	

Check = Preferred or Equal

#7 Heritage Path to Future Planet Detection/Characterization Missions

- TPF booklet Chapter 14 discusses the 2 main goals of post-TPF exoplanet research:
  - High spectral resolution measurement of planet atmosphere (& surface ?) constituents
  - Resolved planet images revealing clouds, ice, continents, oceans, or other features
- Spectral information stated to be desirable specifically mentions visible/NIR data
  - This presumed TPF would collect MIR data, but shows that visible/NIR is valued
- Figure 14.2, showing imaging resolution at 10 pc, assumed λ = 0.6 μm, got 360 km baseline for 25 pixels across the exoplanet
  - In the visible, a far smaller optical system baseline can achieve pixels on the planet than in the MIR
    - The 360 km baseline grows to 7200 km for MIR



- The public would probably understand better, and be more inspired by, a visible picture
  - Therefore, important future optical technologies are advanced by reflected-light TPF: large-aperture visible/NIR optics, wavefront improvement and control, various Fourier-optical methods for light suppression, etc.

Implementation Summary/Conclusion

- Future exoplanetary astronomy and astrophysics will be built upon a selection of tools, including:
  - Extremely high-precision large optical systems
  - High contrast imaging
  - Interferometry at all wavelengths
  - Nulling interferometry

- We should imagine each of these technologies extended for decades,until they reach whatever practical limits they might encounter. How do they fit together over the decades? In what order should these activities take place? This is a major task of the study phase we're in.

H: Evaluations and Recommendations

Crocker, Kilston

Evaluation and Scoring Approach
Advantages of Architecture Families
Matrix of Architecture Scores
Prioritized List of Top Architecture Options

The Jim Crocker Story – Blessed Be the Peacemakers

1. We have been surprised by the variety of attractive solutions based on detecting reflected light from exoplanets

2. We have also been surprised by the number of issues where reflected-light solutions seem more attractive than emitted-light solutions

3. We now see TPF's "fork in the road" as the fundamental choice between these two paths

4. Currently unresolved – but resolvable – technology issues make it desirable to keep both potential paths open until their resolution

5. Now we will share our findings and justify our recommendation to push both solution sets hard in the next phase of study

Family Advantages Matrix
(Not Restricted to 7 Criteria)

Family / **Element**	**Emitted Light – MIR (Interferometers)**	**Reflected Light – Vis./NIR (Coronagraphs)**
Science	Lower total star-planet contrast Planet spectral features (possibly) Planet temperature measures Planet phases less variable Angular resol. of discrete objects Penetration, viewing MW, other dust Little overlap with ground scopes	Lower risk of confusion impact Imaging quality over wide FOV **Images and spectra capture rate** Information in planet phases Can see cold large planets Upgradeable, **multi-uses, UV**
Implementation	Technology for future IR IFs (PI?) **Lower surface quality needed** Adjustable baseline – match planets Less sensitive to scattering, contam. Less sensitive to micrometeorites Design interests and inspires public	Simpler deployment **No need for constellation control** Less propellant, contamination No cryo systems **Fewer new technologies** **Lower cost**

The Two Main Architecture Families vs. the 7 Criteria

Architecture Family **Criteria**	**Emitted Light – MIR (Interferometers)**	**Reflected Light – Vis./NIR (Coronagraphs)**
1. Sci. - Exoplanets		√
2. Sci. - Astrophysics	√	√
3. Technology		√
4. Cost		√
5. Risk		√
6. Reliability		√
7. Origins Future Path	√	√

Check = Preferred or Equal

How Individual Architectures Were Scored Against Evaluation Criteria

- Per RFP, Decadal Committee guidelines: weigh #1 and #2 equally — **25 each**
  - Criterion #1 was split up: **15** points for planet finding and **10** for characterization
- Weighed criteria #3 - #7 equally, but less heavily than #1 and #2 — **10 each**
- Rejected any architecture scoring a 0 on a criterion (it won't do TPF mission)
- For each criterion, at least one architecture was given the maximum score
- At this stage all scoring is:
  - Relative
  - Subjective
  - Represents best scientific and engineering judgment based on our science and implementation analyses

We counted all the hanging chads too!!

All TPF Architectures in 21 x 9 Matrix

Arch.		Planets	Planets	Astroph.	Technol.	Cost	Risk	Rel./Rob.	Future	TOTAL
#	Architecture Name	1 - Find.	1 - Char.	2	3	4	5	6	7	SCORE
1	**Spergel var.-pupil corona.- 8 m**	**15**	**10**	**23**	**10**	**10**	**10**	**10**	**8**	**96**
2	**Masking coronagraph - 10 m**	**15**	**10**	**25**	**6**	**8**	**6**	**8**	**10**	**88**
3	Nulling coronagraph - 10 m	13	8	20	4	6	4	6	8	69
4	Focal plane phase mask	9	5	10	6	6	4	6	5	51
5	Microtube block	0	0	0	0	0	0	2	0	2
6	Occulting Screens	2	2	1	0	0	0	5	0	10
7	Spergel pinhole screen	2	2	1	0	0	0	5	0	10
8	Interferometer Full-Monolith	3	8	10	4	4	4	5	2	40
9	Interferometer Lite-Monolith	2	4	6	4	6	4	5	2	33
10	Interferometer 2D Tethered	3	3	5	0	3	2	2	4	22
11	Interferometer Linear Tethered	2	2	2	0	3	2	2	4	17
12	**Interf. FF - Chopping Linear DAC**	**5**	**7**	**20**	**6**	**7**	**6**	**6**	**8**	**65**
13	Interferom. FF- Chop.Dual Bracewell	3	2	20	4	7	4	4	6	50
14	**Interf. FF- Laurance Super-Darwin**	**7**	**9**	**23**	**6**	**5**	**6**	**6**	**10**	**72**
15	Interferometer FF - Mariotti triangle	7	9	23	4	5	4	4	6	62
16	Interferometer FF - TPF-Lite	4	3	12	4	6	4	4	6	43
17	Interferometer FF - Fizeau	1	1	8	4	4	4	4	4	30
18	Interferometer FF - Hypertelescope	7	12	14	1	0	0	4	8	46
19	Interfer. FF - Mini - hypertelescope	1	1	4	2	5	0	2	6	21
20	Super-shielded Interferometer	7	9	20	0	1	0	2	6	45
21	**Cable-Car Interferometer DAC**	**4**	**6**	**15**	**6**	**6**	**6**	**6**	**8**	**57**
	Points Possible:	**15**	**10**	**25**	**10**	**10**	**10**	**10**	**10**	**100**

Matrix of Candidate Architectures Scored Against Evaluation Criteria

Architecture:	1. 1 Spergel pupil CG-8	2. 14 Super-Darwin IF	3. 2 Masking CG-10	4. 12 Chop. L. DAC IF	5. 21 Cable-Car IF
15 - Sci.-Planet Find.	15	7	15	5	4
10 - Sci.-Planet Char.	10	9	10	7	6
25 - Sci.-Astrophys.	23	23	25	20	15
10 - Technology	10	6	6	6	6
10 - Cost	10	5	8	7	6
10 - Risk	10	6	6	6	6
10 - Reliability	10	6	8	6	6
10 - Origins Path	8	10	10	8	8
Total Score	**96**	**72**	**88**	**65**	**57**

Prioritized List – TPF Architectures Deemed Suitable for Phase 2 Study

- 1 Spergel pupil CG-8
  - Novel, powerful way to search quickly for "Earth-like" planets and characterize them
  - Can include wide variety of astrophysical instrumentation
  - Apparently most cost-effective ($M / planet), subject to frequency of real "Earths"
- 14 Super-Darwin IF
  - Ranks high due to uniqueness of technologies, and for keeping important options open
  - Requires larger collectors and launcher than Darwin book design; could be very costly
- 2 Masking CG-10
  - Visible-light advantages; larger aperture, gradient mask permit searching close to stars
  - Will study all coronagraphs together; cost-benefit for larger aperture still unclear
- 12 Chopping Linear DAC IF
  - Possibly the most cost-effective of the interferometers, but not as robust as Darwin
  - Might take too long to search 150 stars for planets
- 21 Cable-Car IF
  - An unusual, long-shot concept may stimulate a variety of breakthrough technologies

I: Priority Architecture Description

Epstein

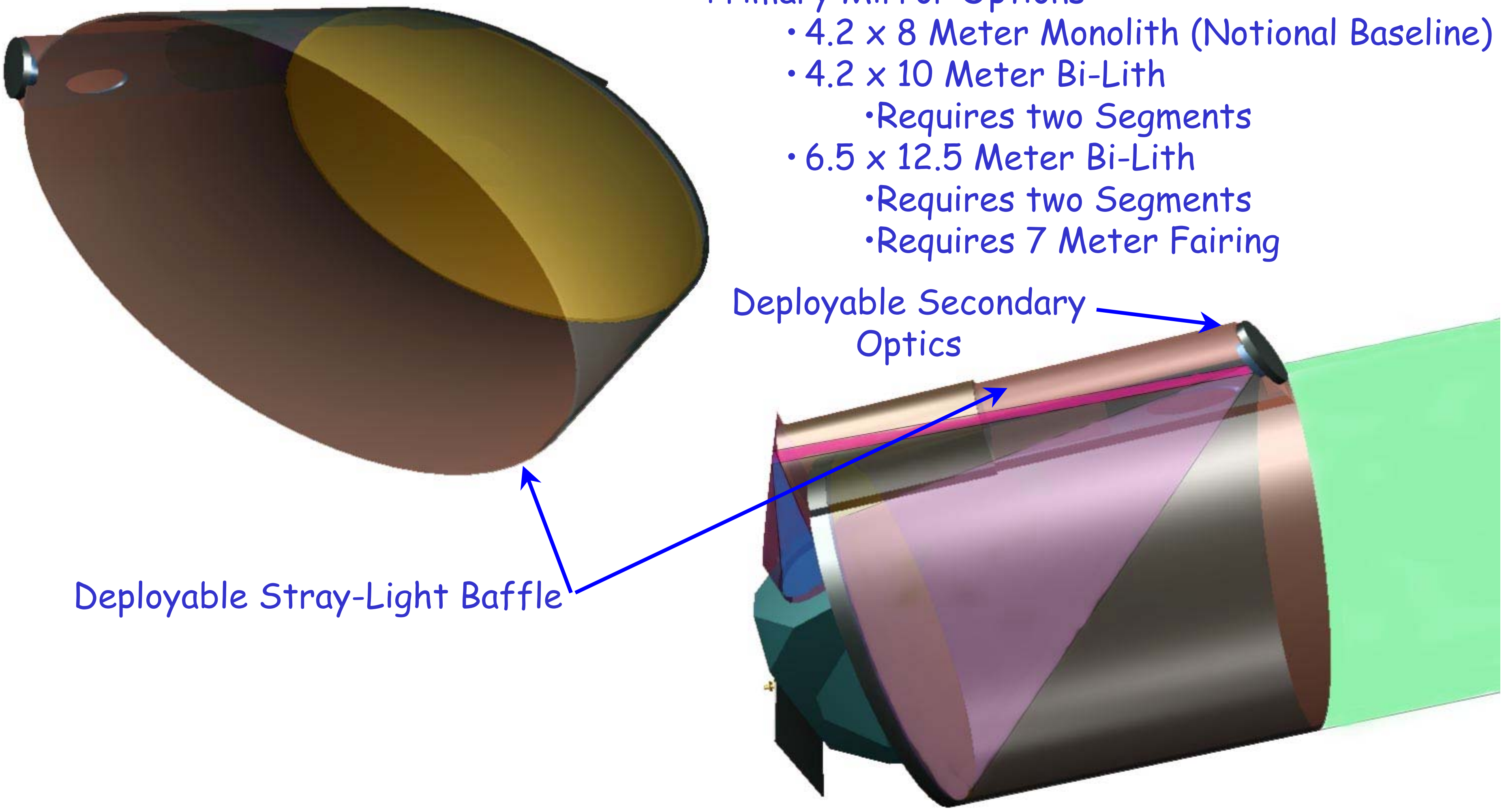
- Coronagraph Implementation
- Spacecraft
- Orbits
- Launch
- Operations
- Implementation Challenges

Coronagraph TPF
#1 Priority Architecture

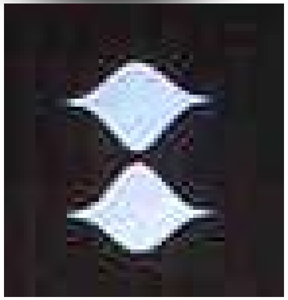
- Visible/NIR coronagraph, single-spacecraft
- Monolith 8.4 m x 4.2 m primary mirror, glass or SiC
  - Can be built and tested with existing facilities, re-use of NGST sites
  - Option, with larger shroud, new polishing facilities, and modified test facilities, to increase mirror size to 12.5 m x 6.5 m (can be bi-lith)
  - Actuators (~300) behind mirror compensate for low-frequency distortions
- Off-axis optical design minimizes scatter and obscuration
- Deployable secondary and baffle tube
- Adaptive optics with deformable mirror
- Spergel pupil currently preferred (could be double, thereby on-axis)
  - A significant advantage of the on-axis design is the large focal plane that would enable astrophysics to be done in parallel mode to the planet characterization
  - Other masks and pupils will be evaluated (possibly combined in a “filter-wheel”)
- Advanced detector array technology for imaging

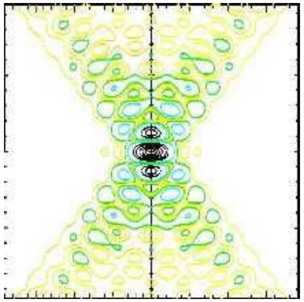
Coronagraph Telescope Optics Notional Concepts

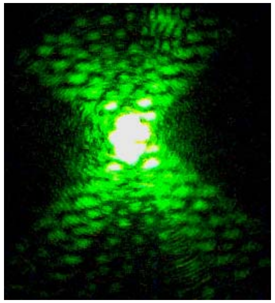
Primary Mirror Options
- 4.2 x 8 Meter Monolith (Notional Baseline)
- 4.2 x 10 Meter Bi-Lith
  - Requires two Segments
- 6.5 x 12.5 Meter Bi-Lith
  - Requires two Segments
  - Requires 7 Meter Fairing

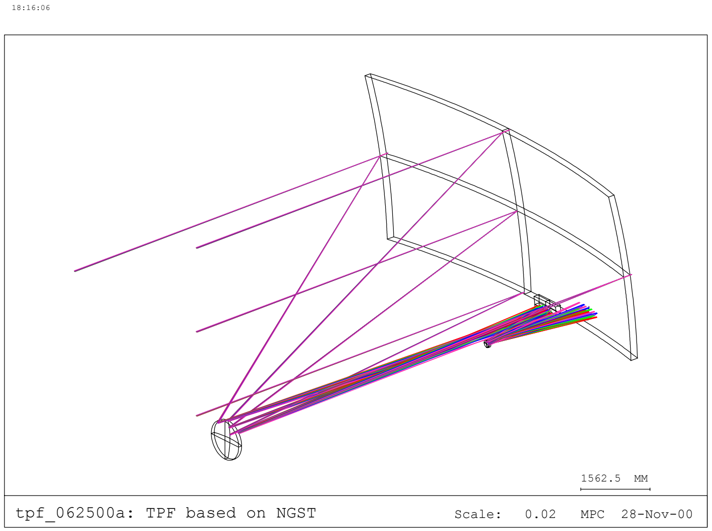


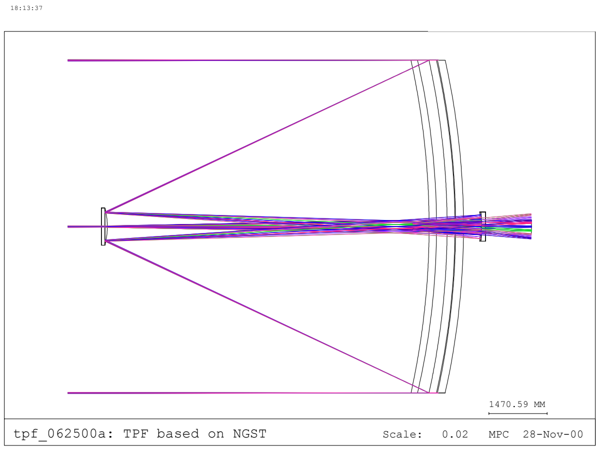
Coronagraph Instrument (Spergel Pupil, or Off-Axis and Other Masks)

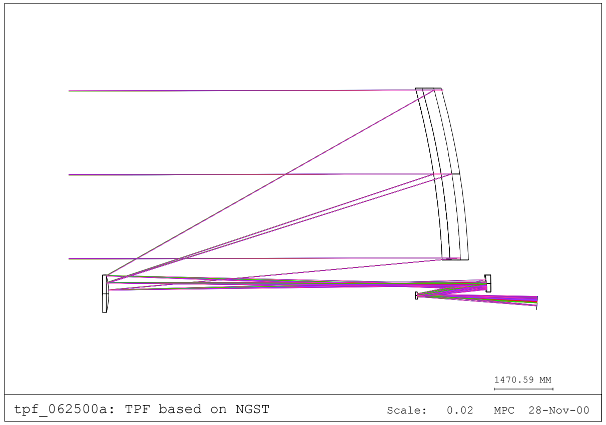

Spergel pupil


PSF (theor.)


1st Lab Demo



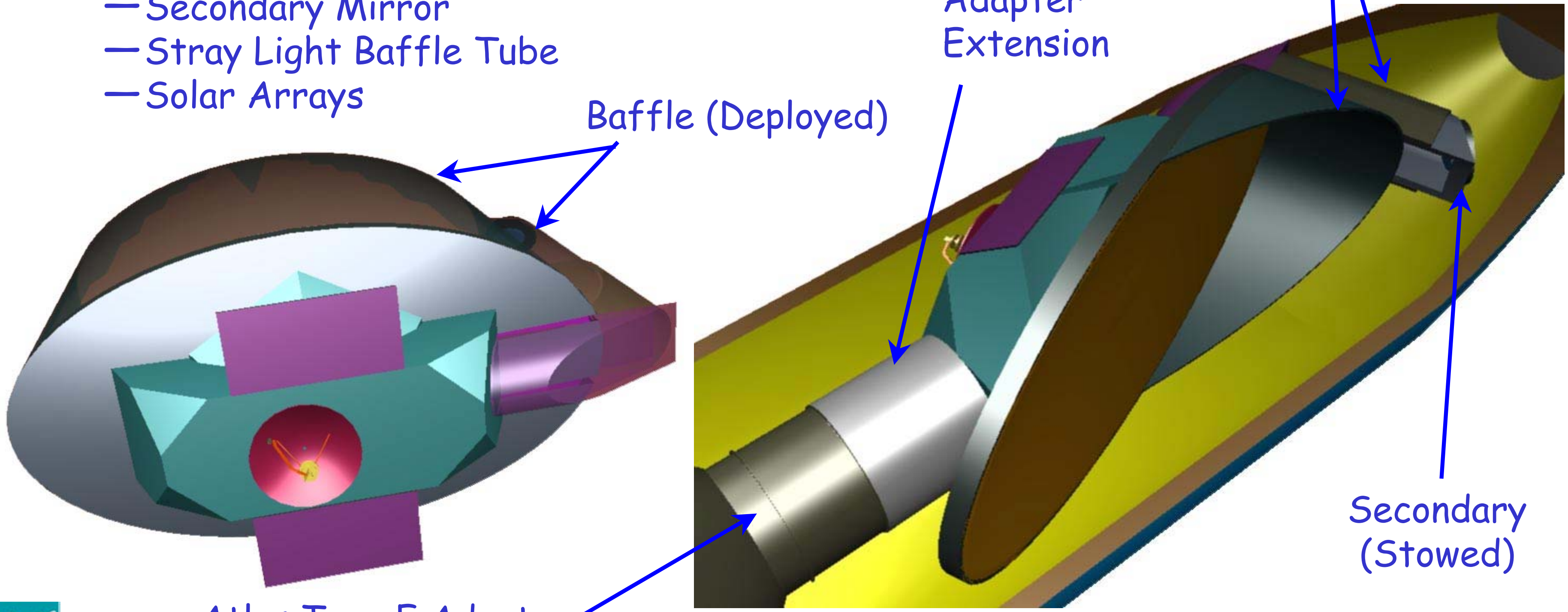




Coronagraph Spacecraft (Bus)

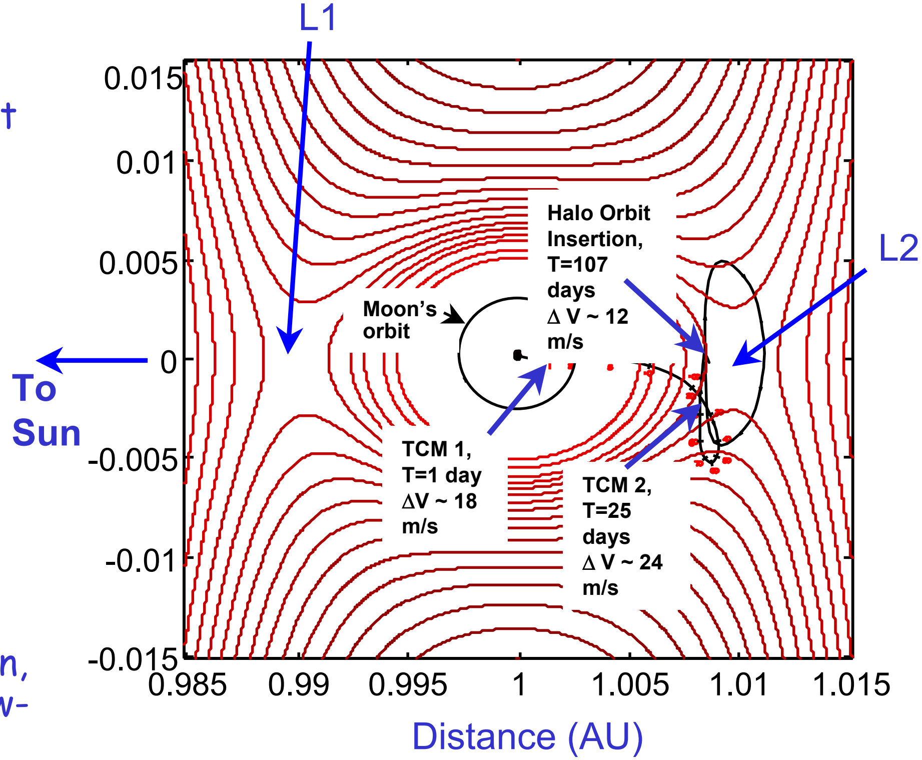
Bus Overview (Notional Concept)

- Precision Pointing & Stability (~ 1 mas = 5 nanoradians)
  - Evolved from NGST Designs (non-cryo)
- Two-Axis Tracking 2-Meter High Gain (X or Ka)
- Single-Axis Tracking Solar Array (fixed to be traded)
- Deployment Mechanisms
  - Secondary Mirror
  - Stray Light Baffle Tube
  - Solar Arrays



Coronagraph Orbit Scenarios

- L2 Halo Orbit (Notional Baseline)
  - Provide ΔV to correct for launch vehicle direct transfer insertion error
  - Provide ΔV to insert spacecraft into orbit about L2
  - Provide orbit maintenance at L2 for 10 years
  - Provide 3-axis attitude control during ΔV maneuvers and provide momentum wheel unloading for 10 years
- Optional Orbits (Further Study in Next Phase)
  - Out-of-Ecliptic Orbit (Princeton orbit)
    - Reduces Zodi brightness
  - LEO orbit option
    - Cheaper launch, mass margin, lower radiation, serviceability, longer operating lifetime, new-technology upgrades, more affordable communications link
    - Limited sky coverage, and coordinated with 1-year cycle exoplanets may have

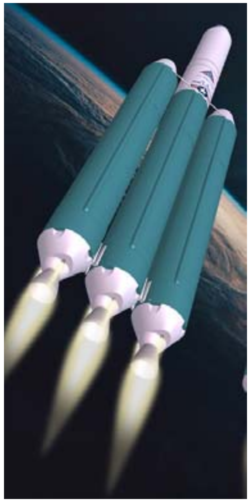


Coronagraph Launch Scenarios

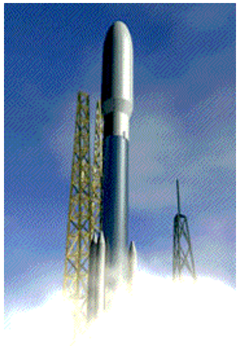
- Utilize Emerging Launch Vehicles
  - Atlas V, Ariane 5, Delta IV, and VentureStar
- Utilize Space Station for On-Orbit Functions
  - Potential for Checkout, Assembly, and Servicing

Space Station

Delta IV

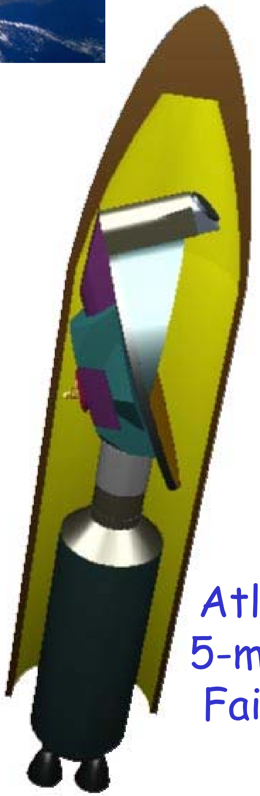


Atlas V



Ariane 5

VentureStar



Atlas V 5-meter Fairing

Coronagraph Launch Capability

Mass Element	NGST Strawman	Coronagraph			Formation Flyers	
		4.2 x 8.4 Monolith	4.2 x 10 Bi-Lith	6.5 x 12.5 Bi-Lith	TPF Book (3 x 4)	Super-Darwin (3 Meter)
Flight Segment						
Spacecraft (Bus)		1,024.0	1,024.0	1,024.0		
Optical Telescope Assy (OTA)		692.4	824.3	1,658.3		
Instrument Elements		571.0	571.0	571.0		
Collector Spacecraft					2,920.0	3,300.0
Combiner Spacecraft					690.0	725.0
Launch Adapter		70.0	80.0	100.0	450.0	550.0
Contingency (15%)		353.6	374.9	503.0	609.0	686.3
Total	3,000.0	2,711.0	2,874.1	3,856.3	4,669.0	5,261.3
Total Collecting Area (m2)	50.2	27.7	33.0	66.3	37.7	42.4

Atlas V Capabilities	C3=0	C3=0	C3=0	C3=0	C3=0	C3=0
Atlas V 501 (5 Meter Fairing/No Strap Ons)	3,000.0	3,000.0	3,000.0			
Atlas V 511 (3 Meter Fairing/1 Strap Ons)	3,700.0					
Atlas V 531 (3 Meter Fairing/3 Strap Ons)	5,100.0				5,100.0	
Atlas V 551 (5 Meter Fairing/5 Strap Ons)	6,500.0					
Atlas V 701 (7 Meter Fairing/No Strap Ons)	2,900.0					
Atlas V 721 (7 Meter Fairing/2 Strap Ons)	4,260.0			4,260.0		
Atlas V 741 (7 Meter Fairing/4 Strap Ons)	5,620.0					5,620.0
Atlas V 751 (7 Meter Fairing/5 Strap Ons)	6,300.0					

Coronagraph Operations

- Data Volume
  - Science Data
    - 1 Gbits/day *(planet-finding, further study in next phase)*
    - Up to 500 Gbits/day *(astrophysics, further study in next phase)*
  - Engineering Data
    - 32 kbps
- Ground Station (Notional Baseline)
  - L2 support (evolved from NGST Ground Station Data) Communications (X or Ka Band)
    - One or Two Ground Stations
  - Further Study on Alternate Orbits

Concerns with Large Coronagraph Implementation

- Engineering issues
  - Size of DM
  - Stability of DM
  - Stability of optics at high frequency
  - Ability to fabricate smooth masks
  - Spectrometer implementation
  - Detector properties (including radiation environment)

- *LEO orbit option*
  - *Cheaper launch, mass margin, lower radiation, serviceability, longer operating lifetime, new-technology upgrades, more affordable communications link*
  - *Limited sky coverage*
    - *Short integration times in certain directions*
    - *Observing windows may be mis-coordinated with 1-year cycles common for exoplanets*

J: Requirements, Modifications, and Mission Precursors

Noecker

Benefits if Science Requirements Relaxed

Utility of Mission Precursors

Major Benefits if Science Requirements Relaxed or Modified, but Preserving Origins Goals

- Concentrating only on planet-finding mission reduces total integration times needed and covers more stars during TPF operating lifetime
  - Right decision if Earth-sized planets turn out to be very rare
  - System apertures (and complexity and cost) might also be reduced
  - A subsequent mission could be better planned to meet the TPF planet spectroscopy and Life Finder requirements
  - Reduces risk in the Planet Finder program

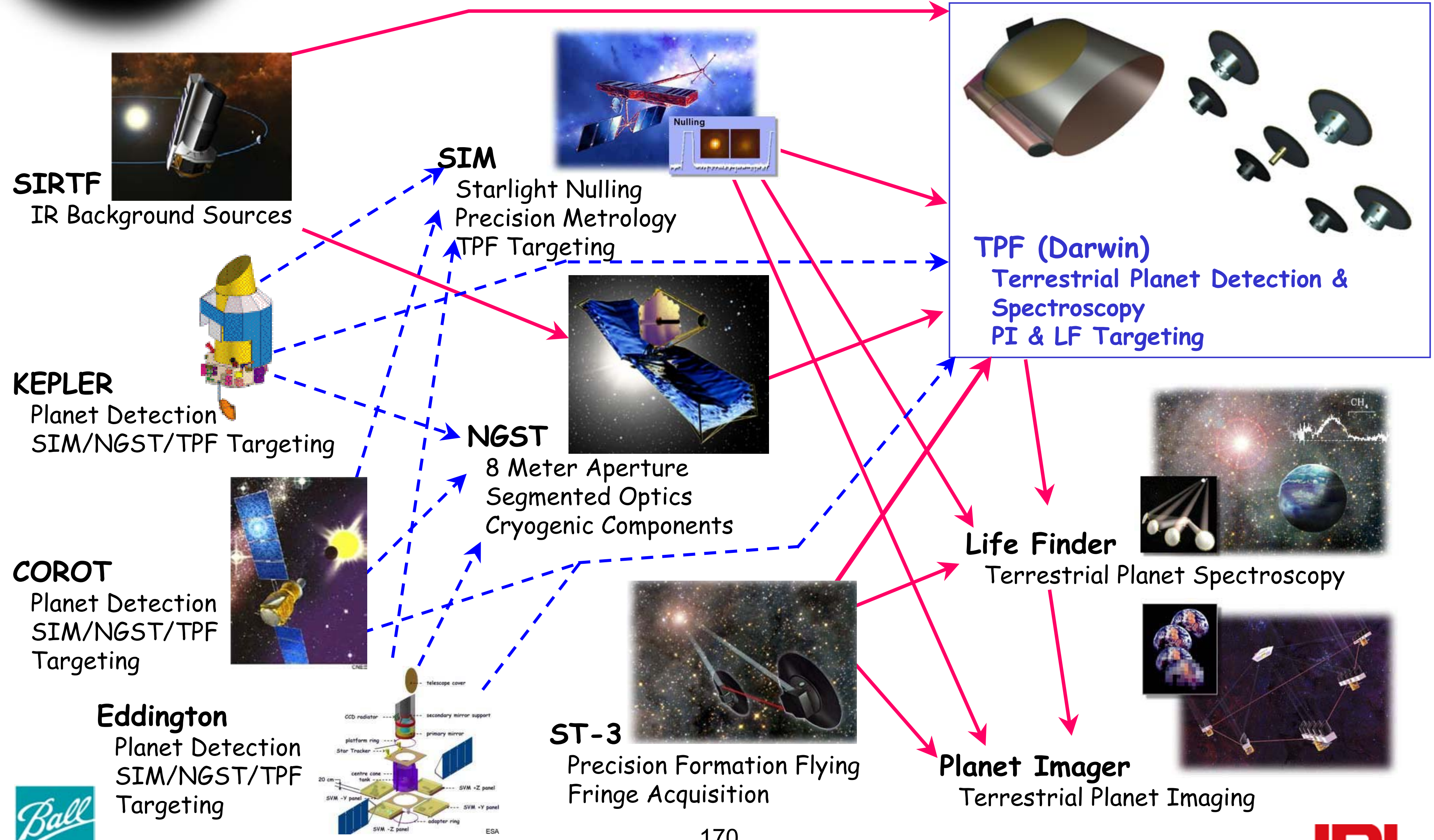
- Reducing the number of stars to be surveyed (below 150)
  - Can use a smaller system requiring greater integration times

- Relaxing the 0.75 mas resolution
  - Interferometer: can operate at smaller baselines with brighter guide stars
    - Monolith or quasi-monolith interferometers do the job
  - Coronagraphs enter the astrophysics picture

Utility of "TPF" Precursor Missions and Description of Such Concepts

- Major benefits to TPF possible with precursor missions
  - Acquiring data on frequency and circumstances expected for Earth-like planets
    - If planets rare, TPF mission success will rest on searching efficiently
    - Characterizing typical exozodi disk densities and confusion reduces risk
      - Keck, LBT, VLT, SIRTF, and NGST should add to our knowledge in these areas
- Developing and proving technologies needed to reduce risk for TPF options
- Description of new potential precursor missions of value to TPF
  - Kepler and Eddington missions to find planet transits in large sample of stars
    - Stares for years at wide-angle sky patch; very high photometric accuracy
    - Determines "local" Earth-like planets' typical frequency, radii, and orbits
  - Eclipse mission can validate performance of coronagraph with adaptive optics

Utility of “TPF” Precursor Missions, and Technology Flow to the Future



SIRTF
IR Background Sources

KEPLER
Planet Detection
SIM/NGST/TPF Targeting

COROT
Planet Detection
SIM/NGST/TPF
Targeting

Eddington
Planet Detection
SIM/NGST/TPF
Targeting

SIM
Starlight Nulling
Precision Metrology
TPF Targeting

NGST
8 Meter Aperture
Segmented Optics
Cryogenic Components

ST-3
Precision Formation Flying
Fringe Acquisition

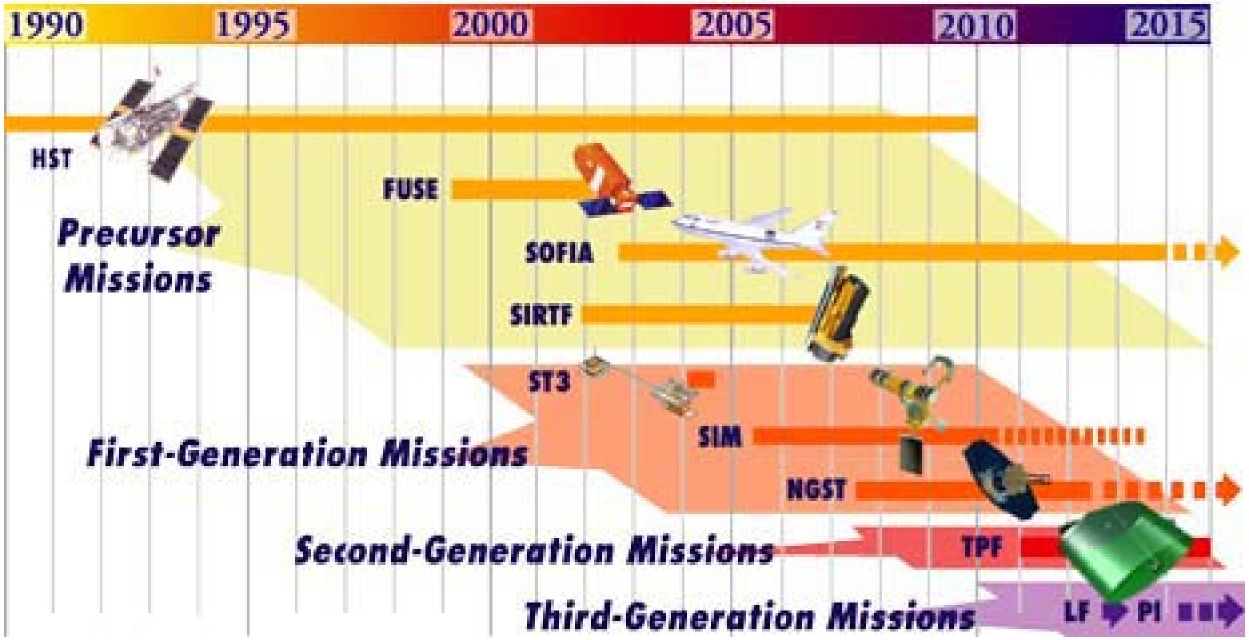
TPF (Darwin)
Terrestrial Planet Detection &
Spectroscopy
PI & LF Targeting

Life Finder
Terrestrial Planet Spectroscopy

Planet Imager
Terrestrial Planet Imaging

Utility of "TPF" Precursor Missions and Description of Such Concepts

- Major benefits to TPF possible with precursor missions
  - Acquiring data on frequency and circumstances expected for Earth-like planets
    - If they are sufficiently rare, mission success will depend on searching as quickly, efficiently, deeply, etc. as possible; will be mainly in search mode
  - Developing and proving technologies needed to reduce risk for TPF options



K: Summary

Kilston

Summary of Main Architecture Issue

- Planet detection approach is driven by star being 20 times as hot as planet
  - Therefore two wavelength regions available, one ~ 0.5 μm and one ~ 10 μm
- Short wavelengths can achieve angle performance with a smaller system
  - In a single dish telescope, coronagraph easiest way to reduce stellar leakage
  - CG better for nearby stars, to get angular separation of several Airy radii
- Long wavelengths need large baseline for good angle performance
  - Interferometer can increase baseline, but more complex, several spacecraft
  - Baseline is limited, because resolving stellar disk yields incomplete nulling
  - Interferometers better on more distant stars and for seeing close-in to stars
- Performance limitations
  - Reflected-light options are limited by errors in the telescope
  - Emitted-light options are limited by emission of whatever else is bright
  - Best coronagraph design > 3 x shorter integration time than best MIR one (emission cases are all dominated by either local zodi or exozodi)
  - Probably more desirable to have biggest problems locally in hardware than to have them in the system under observation

Conclusions

- A very wide range of TPF architectures were addressed, in 2 families:
  - Reflected-light (mainly coronagraphs)
  - Emitted-light (mainly interferometers)
  - Several new inventions and concepts proved to have significant potential

- Important analyses helped us thoroughly understand the problem
  - Signal-to-noise ratio performance, integration times, and science throughput
  - Biomarker detectability
  - Habitable-zone geometry implications for viewing Earth-like planets orbiting actual nearby FGK stars
  - Unique astrophysics capabilities
  - Implementation challenges: technology, cost, risk, reliability and robustness
  - Technology path to future missions, possible mission reduction, precursors

- Architectures offering the best cost-benefit ratios were identified
  - A visible/NIR coronagraph may find the most nearby planets per $
  - It is not yet clear whether a coronagraph or an MIR interferometer are preferable for implementation, planet characterization, or astrophysics

Errata in Ball TPF Team Preliminary Architecture Review Book

Page	New Entry for Presentation on Dec. 13, 2000
9	[replaced “sees less noise” with] “can be made to see less noise”
15	[Bob Brown’s role] “Principal Scientist”
38	[Resolution] “10 mas”
40	[Sketch should show only one star as what is being observed]
48	[Planet imaging] “may use”
53	[Added definition] “Degenerate Angel Cross (DAC).”
58	[Sketch should show beams entering beneath combiner sun shield]
61	[achromatic null >] “ 10^5 ” ; [Orbit, additional entry] 5 AU
66	[Sketch shows added single-sunshield option and callout]
84	[replaced “1331” with] “DAC”
85	[changed “R = 3” to] “R = 10” ; [200] “ m^2 ”; [replaced “1331” with] “DAC”
86	[replaced last sub-sub-bullet with] “Only indicators in the visible at low spectral resolution are O_2 and O_3”
92	[replaced “1331” with] “DAC”
142	[replaced “TPF Book” with] “Dual DAC”
165	[changed 1 “Gbits”] “Gbit”