

Technology and Design of an Infrared Interferometer for the Terrestrial Planet Finder

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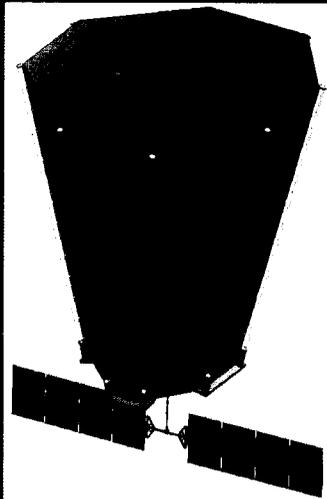
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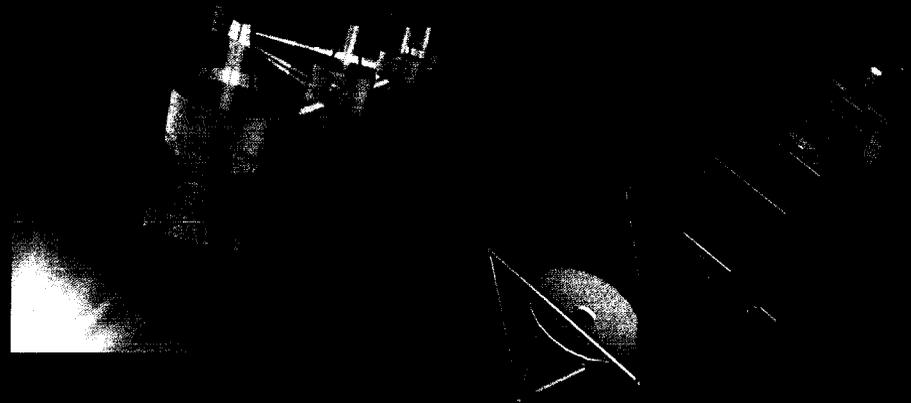
The Search for Habitable Planets



Mission Concept Downselect -- Choose between:



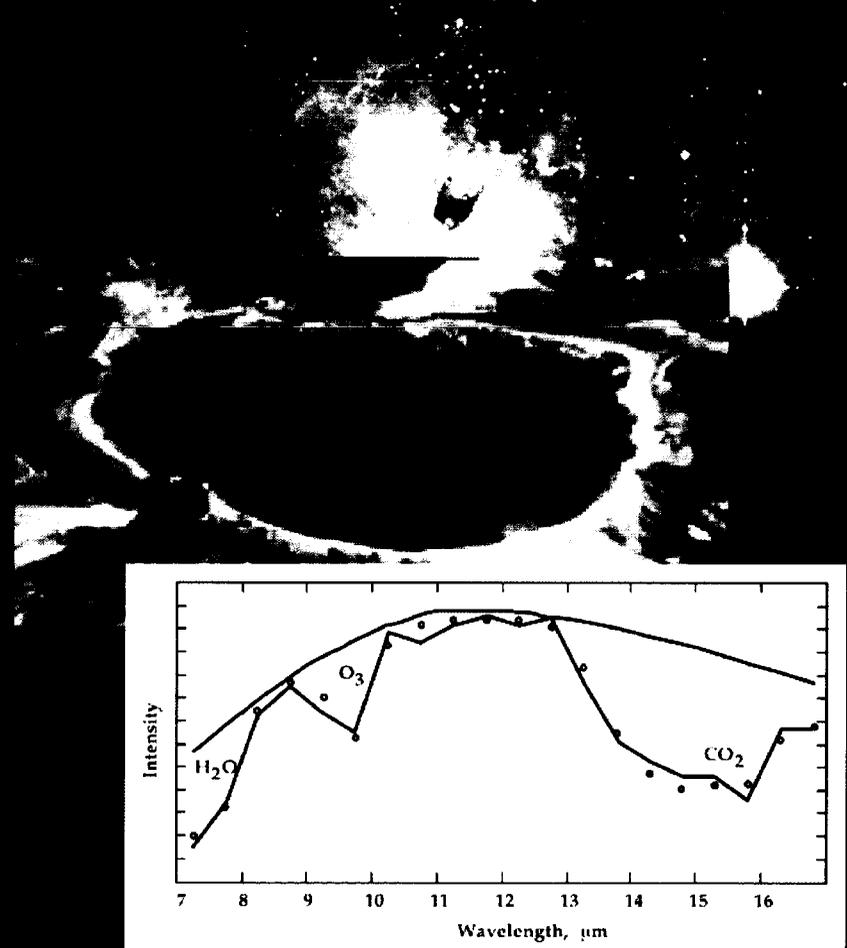
Visible / NIR
Coronagraph



Mid-IR Interferometers

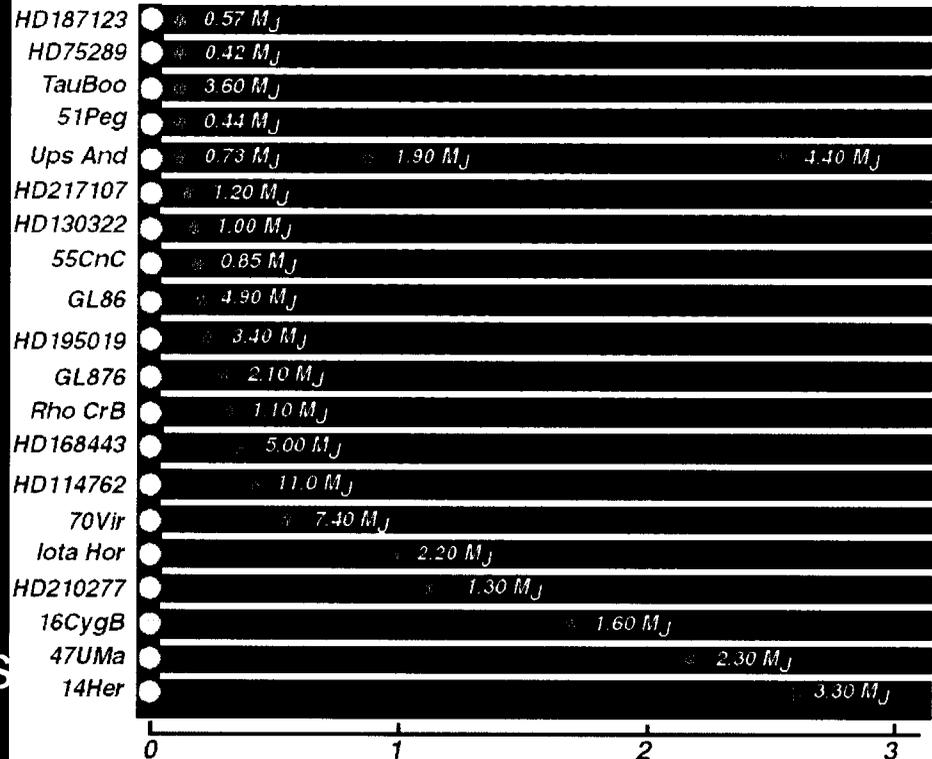
Fundamentals Regarding the Search for Planets and Life

- The necessary ingredients of life are widespread
- Life on Earth can inhabit harsh environments
- Life affects a planetary environment in a detectable way
- Planets are a common outcome of star formation



Gas Giant Planets

- Over 100 planets found using radial velocity wobble
 - ~10% of stars have planets
 - Most orbits < 2-3 AU
 - Half may be multiple systems



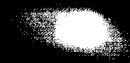
- Planets on longer periods starting to be identified
 - 55 Cancri is solar system analog
- Astrometry (SIM) and radial velocity will determine solar system architecture to few M_⊕



Marcy et al.

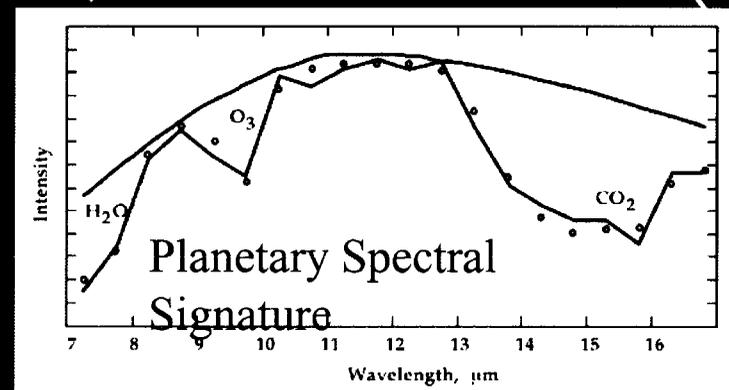
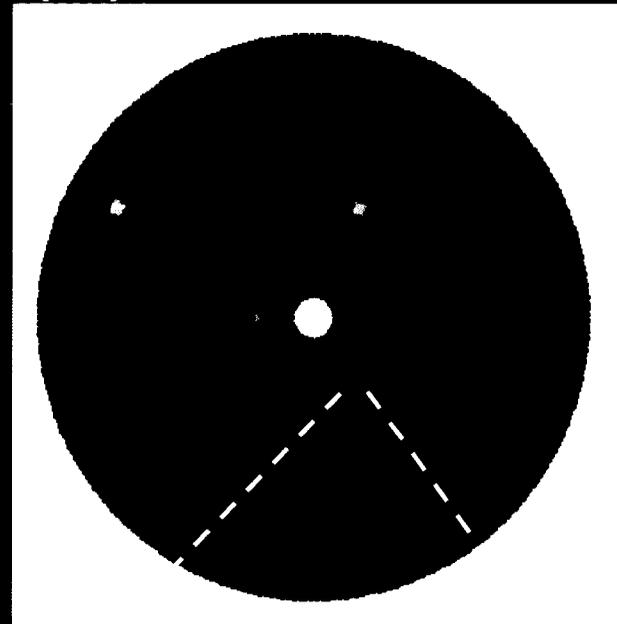
TPF Science (1)

- Detect and characterize terrestrial-sized planets around nearby stars
- Complete survey within 2 yrs:
 - Late F,G,K dwarf stars
 - Full Survey on >30 stars
 - Partial Survey on >120 stars
 - Full survey on >150 stars
- Survey Detection Parameters:
 - Completeness 95%
 - Continuously Habitable Zone:
 - 0.7 to 1.5 AU (G-dwarf) – Earth albedo, One Earth surface area
 - 0.9 to 1.1 AU (G-type) – Earth albedo, half Earth surface area
 - At least 3 visits
- Large Field of View (0.5 to 1 arcsec) to characterize Jovian planets in subset of stars



TPF Science (2)

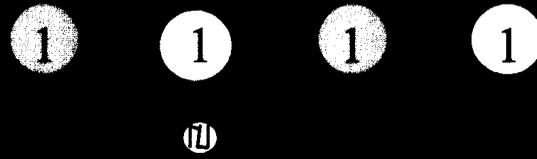
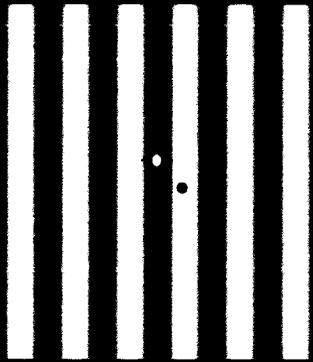
- Obtain Spectra: determine the presence of an atmosphere
- Detect:
 - Water
 - Carbon Dioxide
 - Oxygen 10zone
 - Methane
- Wavelength:
 - 6.5 - 13 μm (17 desirable), SR=25
 - 0.5 - 0.8 μm (1.05 desirable), SR= 75
- Spectral resolution of $R > 100$ for brightest sources
- Desire detection of Rayleigh scattering, absorption edges of photosynthetic pigments.



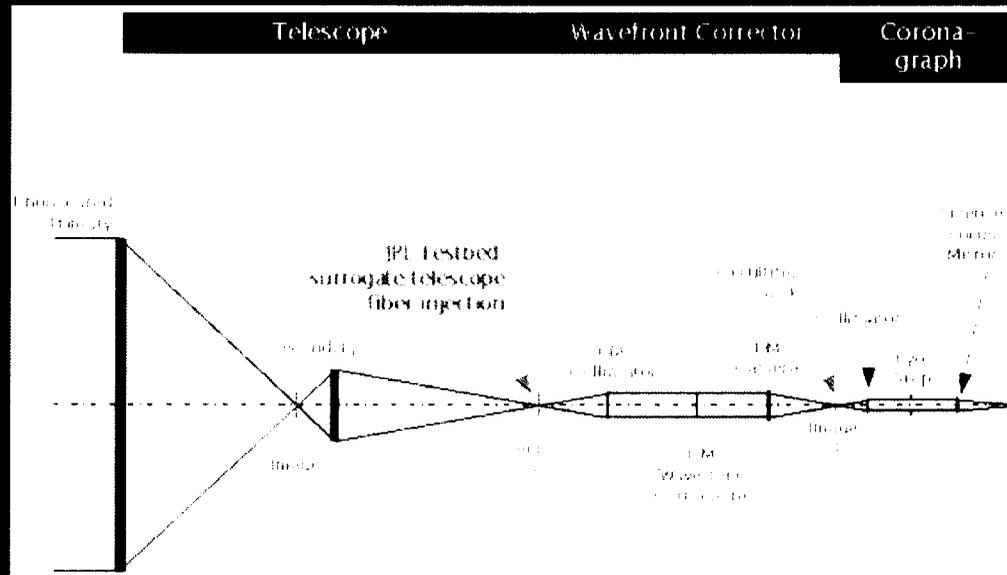
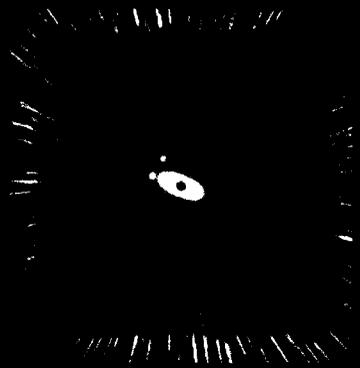
Four Hard Things About TPF

- Sensitivity (relatively easy)
 - Detection in hours, days → spectroscopy in days, weeks .
 - Integration time \propto (distance/diameter)⁴
 - Need 12 m² of collecting area (≥ 4 m) for star at ~ 10 pc
- Angular resolution (hard)
 - 100 mas is enough to see ~ 25 stars, but requires ≥ 4 m coronagraph or ≥ 20 m interferometer
 - Baseline or (aperture) \propto distance
- Starlight suppression (hard to very hard)
 - 10^{-6} in the mid-IR
 - 10^{-10} in the visible/near-IR
- Solar neighborhood is sparsely populated
 - Fraction of stars with Earths (in habitable zone) unknown
 - Unknown how far we need to look to ensure success
 - Surveying substantial number of stars means looking to ~ 15 pc

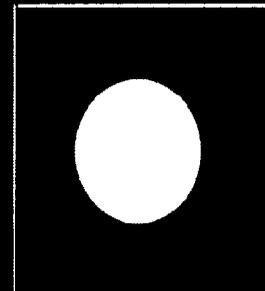
Instrument Approaches



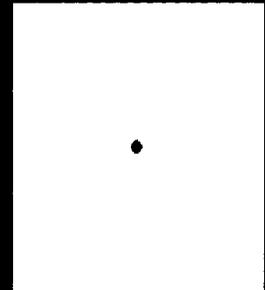
- Shift phase of one input beam by π rad
- Rotate Array
- Chop the pairs



Apodized lyot



Apodized occulting mask



TPF Coronagraph straw man (minimum mission)

Instruments:
Coronagraph Sensor
and Spectrograph
•Wavefront Sensing
and Control
•Masks and Stops and
alternatives

Active Dynamic Isolation

Thermal Isolation

Communication Antenna

Instrument Electronics

Deployed Secondary
w/tower, laser metrology
and 6 DOF actuators

Deployed Telescope
Baffle/Inner Thermal
Shield

Deployed V-groove Thermal
Shields (4 plus telescope
baffle) - 3 degree
separation between layers

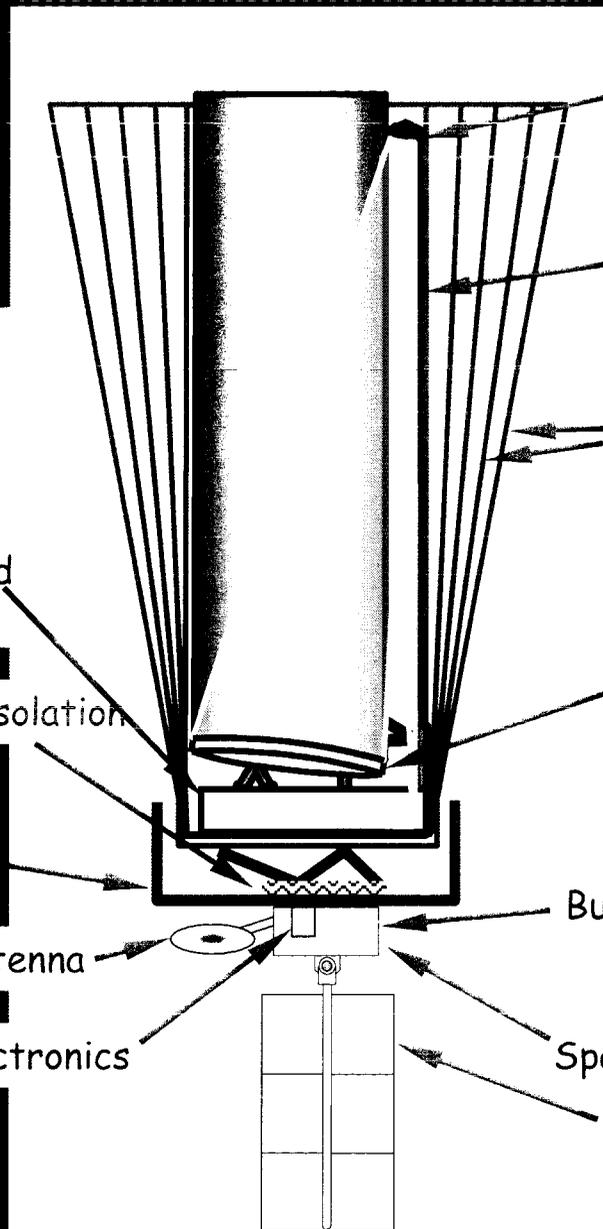
Primary mirror: 6m x 3.5m
(3.5 m dimension shown)
- active surface
correction
possible

Active thermal control for
20C operation

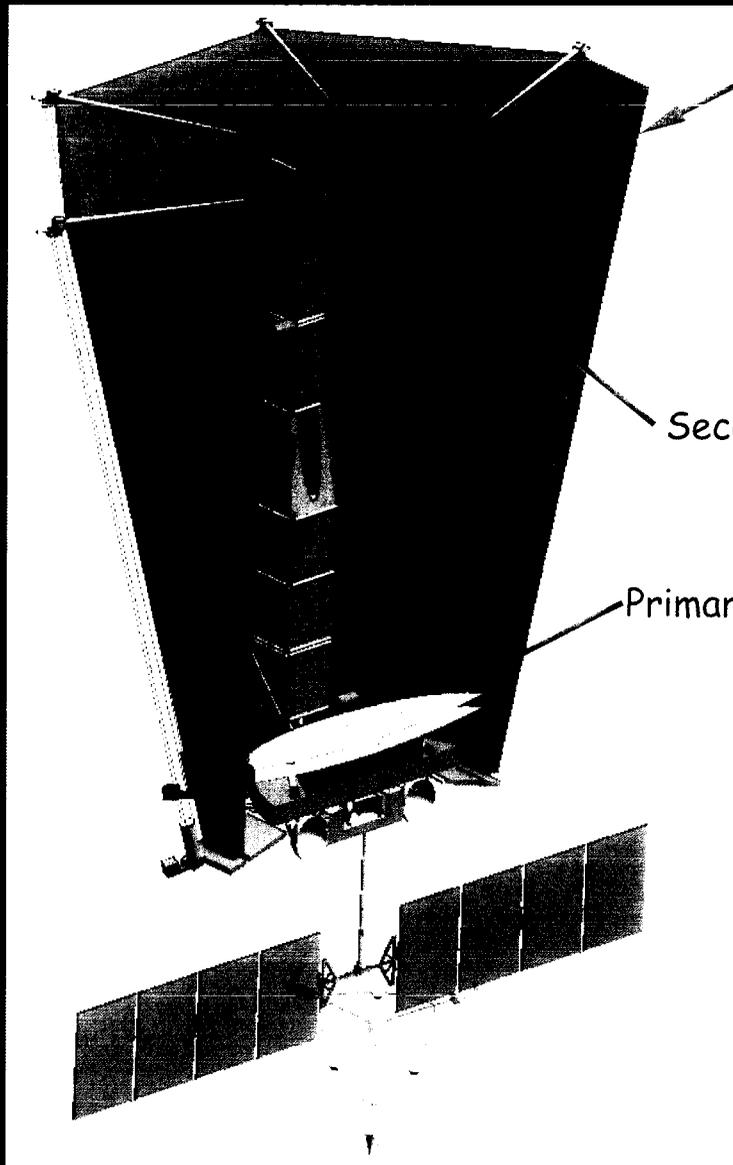
Bus

Spacecraft

Deployed Solar Array
(10 m²)



TPF Coronagraph Conceptual Design

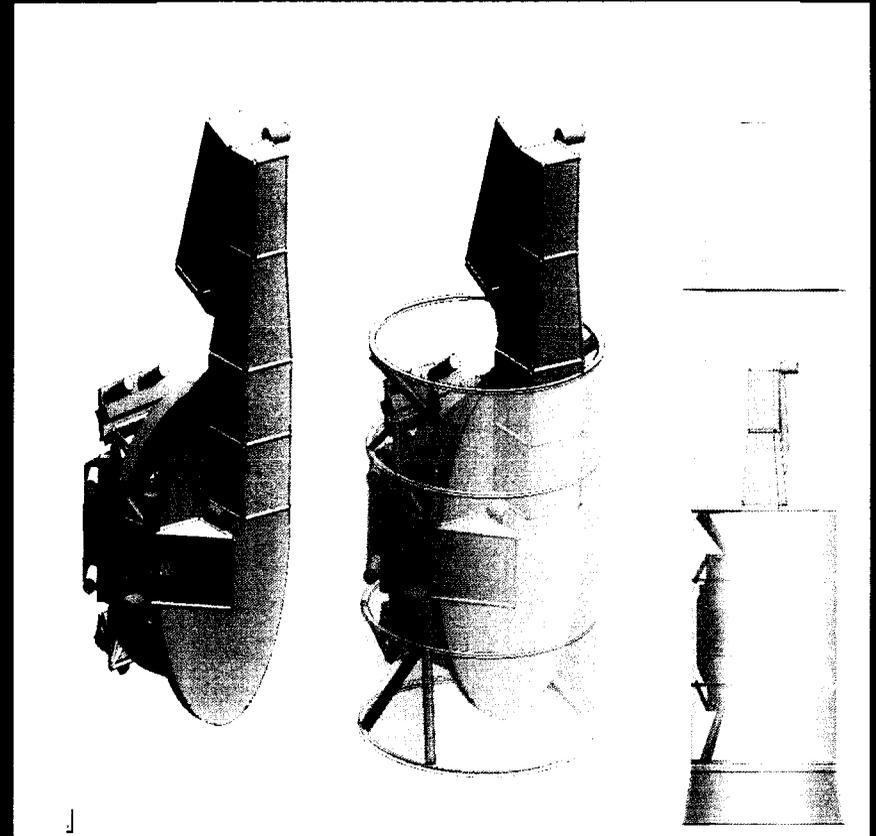


V-groove thermal shields

Secondary

Primary mirror

Sequence for stowing in launch shroud – Delta IV Heavy



Interferometer Systems

Will Deliver

concept for the
full TPF science

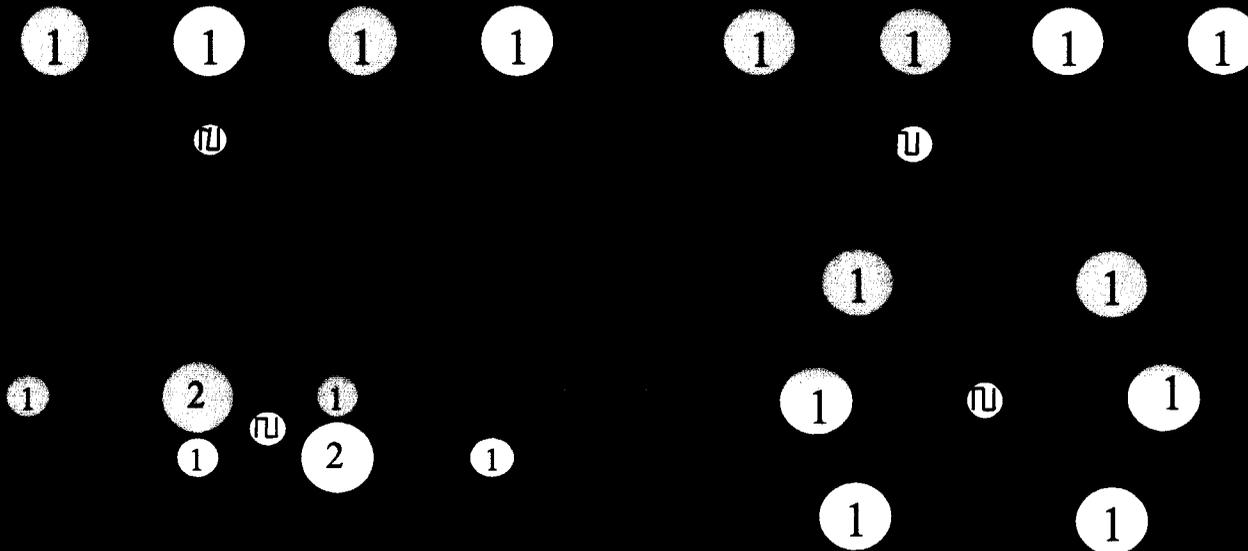
concept for the
minimum TPF science

end-to-end, end-to-end, and
to demonstrate
viability of concepts



Architecture Trades

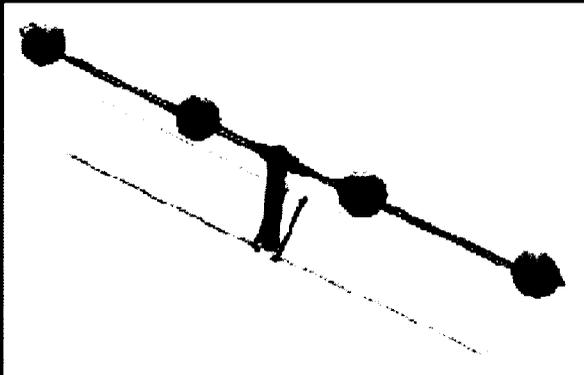
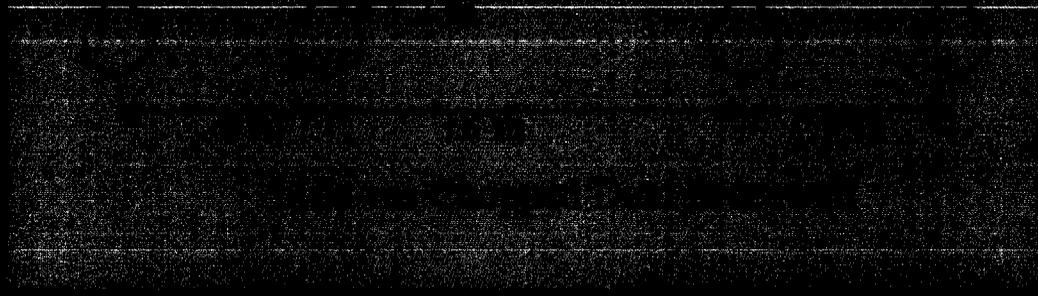
- Considered many different nulling architectures
- Narrowed trade space to those below by considering
 - Exo zodi suppression
 - Instrument background suppression
 - Feasible beam combiner



Architecture Trades

- Figures of Merit
 - Total number of stars surveyed
 - Number of nearby stars (<5 parsec)
- Considered
 - Resolution vs null width (stellar suppression)
 - Sensitivity (limited integration time)
 - Feasible aperture sizes, limited by fairing
 - ~ 3.5m for
 - ~ 3.0 to 3.5 for
 - Feasible structure sizes, limited by fairing
 - ~40-50m

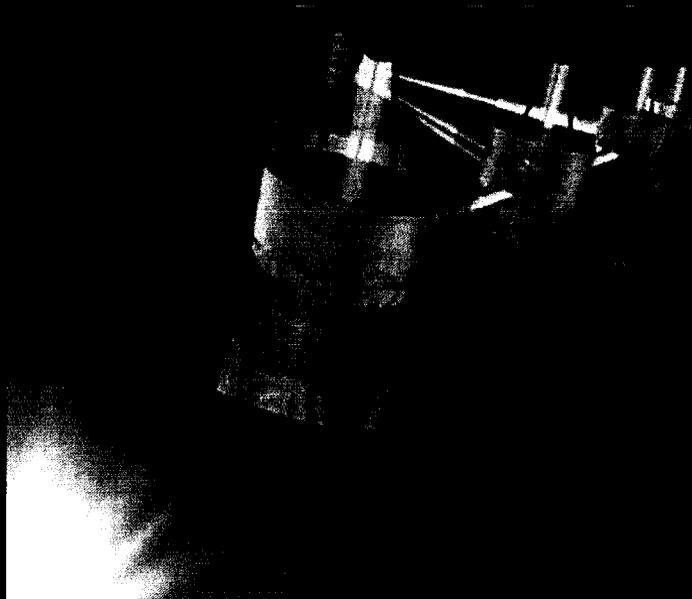
Structurally – Connected Baseline Configuration



SCI – limited by
resolution

- Dual Chopped Bracewell – greatest resolution for given array size
- Array Length: 36m
- 3.2m diameter apertures (Quantity 4)
- ± 45 degrees sky coverage (from anti-sun)
- ~ 50 stars surveyed

Collaboration on TPF/Darwin



ALCATEL

FFI

Configuration Trades

| Design Feature | Minimum Science Mission | Full Science Mission | | | |
|-----------------|-----------------------------|------------------------------|-----------------------------|-----------------------------|-----------------------------|
| | | (A) | (B) | (C) | (D) |
| Platform | Connected Structure | Formation Flying | Formation Flying | Formation Flying | Formation Flying |
| Input pupil | Dual Bracewell | Dual Bracewell | Dual Bracewell | Degenerate Angel Cross | Darwin 2-D bow-tie |
| Array size | 36m | 70m | 70m | 70m | 55m |
| Collecting Area | 4 x 3.2m diameter apertures | 4 x 3.0m diameters apertures | 4 x 4.0m diameter apertures | 4 x 3.0m diameter apertures | 6 x 2.0m diameter apertures |
| No. of Launches | 1 | 1 | 1 | 1 | 1 |

limited by sensitivity.

IR Interferometer: Top Technical Concerns

- Concerns Prioritized by
 - Gap (Seriousness)
 - Urgency
 - Trend

Mitigated by

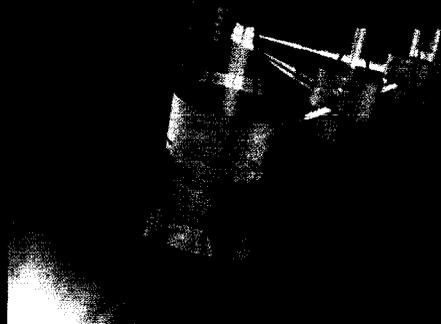
- Inheritance
- System Engineering
- Technology Development

Top Concerns: Core Interferometry

| Category | Primary Concern | TPF Requirement |
|--------------------------------|--|---|
| Starlight Nulling Beamtrain | Nulling architecture | Survey 30-150 stars for terrestrial planets |
| | Beam combination | 4 or 6 beams, 10^{-5} null 6.5- 17 μ m |
| | Internal thermal emissions | $\ll 100$ photons/sec |
| | Spatial Filters | 70% throughput in single mode, 6.5-17 μ m |
| | Intensity matching | 0.2% |
| | Phase control | 1nm (all frequencies) |
| Instrument Controls | Pointing control accuracy of compressed beam | 50 mas |
| | Cryogenic delay line closed loop stability | 0.1 nm at 40K |
| Detectors | Cryocoolers | 30mW at 6K |

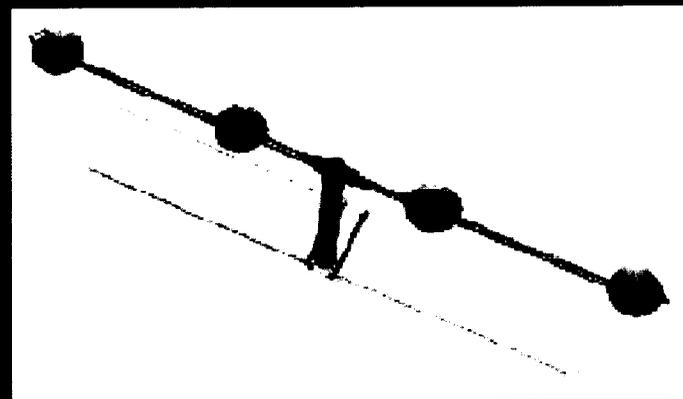
Top Concerns: Formation-Flying

| Category | Primary Concerns | TPF Requirements |
|--------------------------------|--|--|
| Formation-Flying System | Long-term system robustness | 5-10 years |
| | Performance of fine formation control | 1 cm range, 20 arcsec bearing accuracy |
| | Algorithm functionality In deep space | 5 s/c autonomous sensing collision avoidance performance |
| | Course acquisition sensor | 50 cm, 1 deg, 4π steradian FOV with no calibration maneuvers |
| Formation Flying Accommodation | RF interference from thermal shield | Low multipath effects on RF range measurements |
| | Inters s/c stray light | $\ll 100$ photons/sec |



Top Concerns: Connected Structure

| Category | Primary Concern | TPF Requirement |
|---|--|--|
| Precision Cryogenic Deployed Structure | Stability of long Cryogenic structure | 1nm/36m40K |
| | Cryo hinge and latch stability | < 100m |
| | Structural modeling tools | Confident prediction of performance |



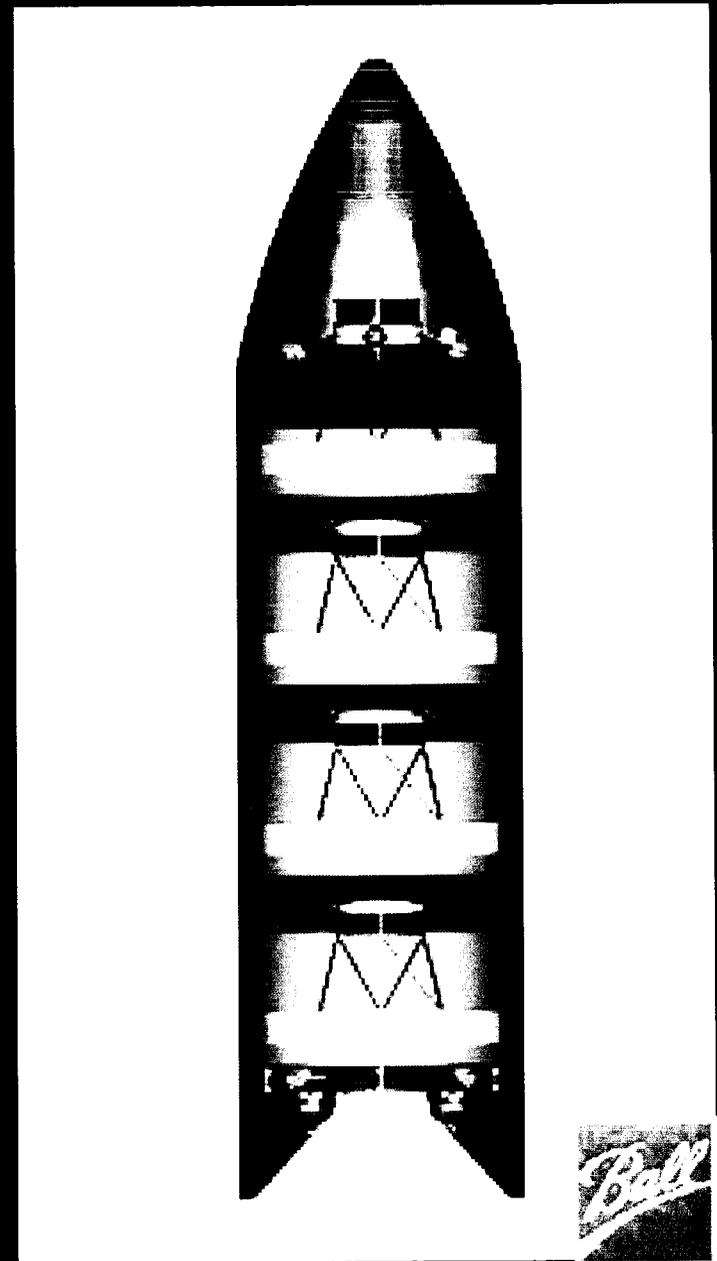
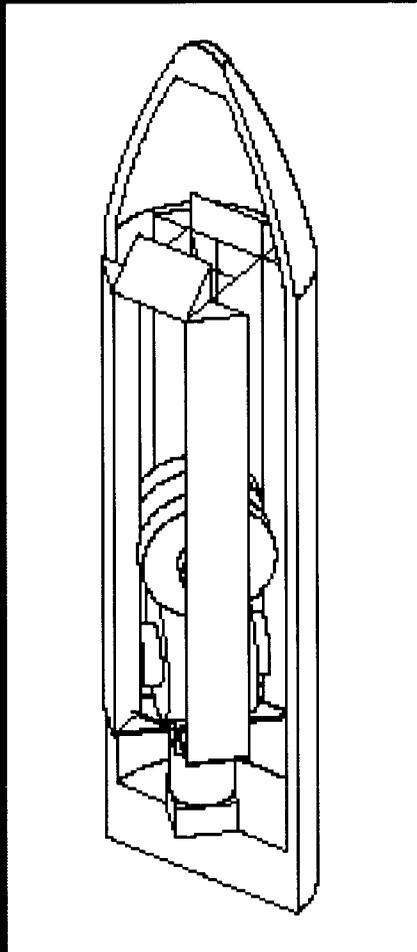
Other Top Concerns

| Category | Primary Concern | TPF Requirement |
|--|---|---|
| Flight & Mission System | Launch packaging of structure, formation flight systems | Self imposed |
| | Interspacecraft communications | Continuous reliable high data rate 4 Mbits/sec |
| | Sky coverage | At least +/- 45 deg |
| Integration and Performance Verification | End to end flight system test | Ability to verify multi-collector distributed flight system |
| | Overall system complexity | Acceptable risk |

System Engineering

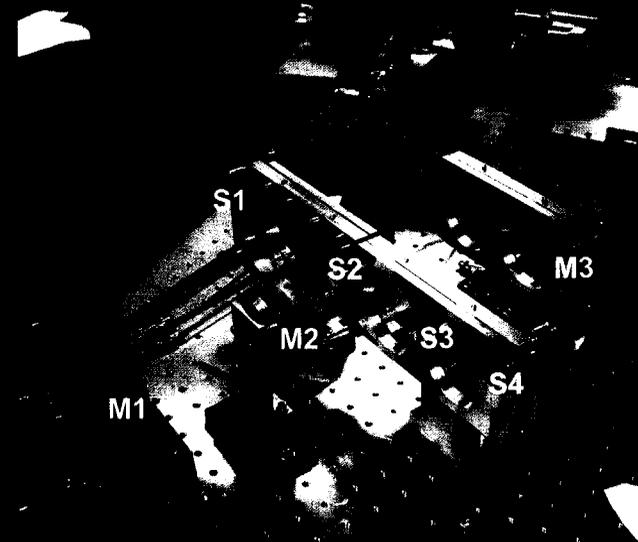
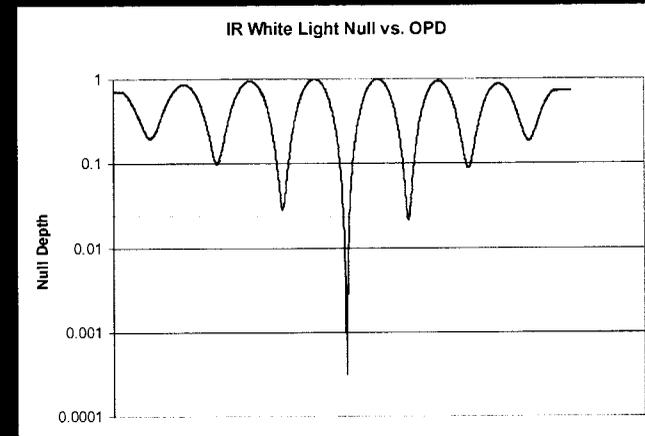
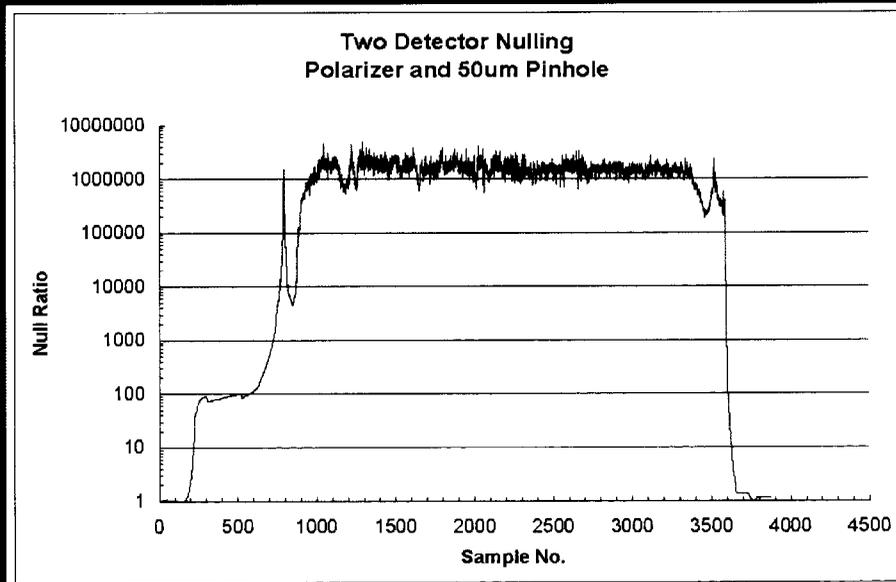
- Orbit: L2
- Launch Vehicle Delta IV Heavy
- Fairing 22.4m
- Power Solar Arrays
- Coarse formation sensor RF
- Open Trades: SCI configuration: 6 fold oblique
 - Sunshield configuration and deployment
 - Telescope optical design
 - Fine pointing control technology
 - Timing of formation or boom deployment

Launch Vehicle packaging



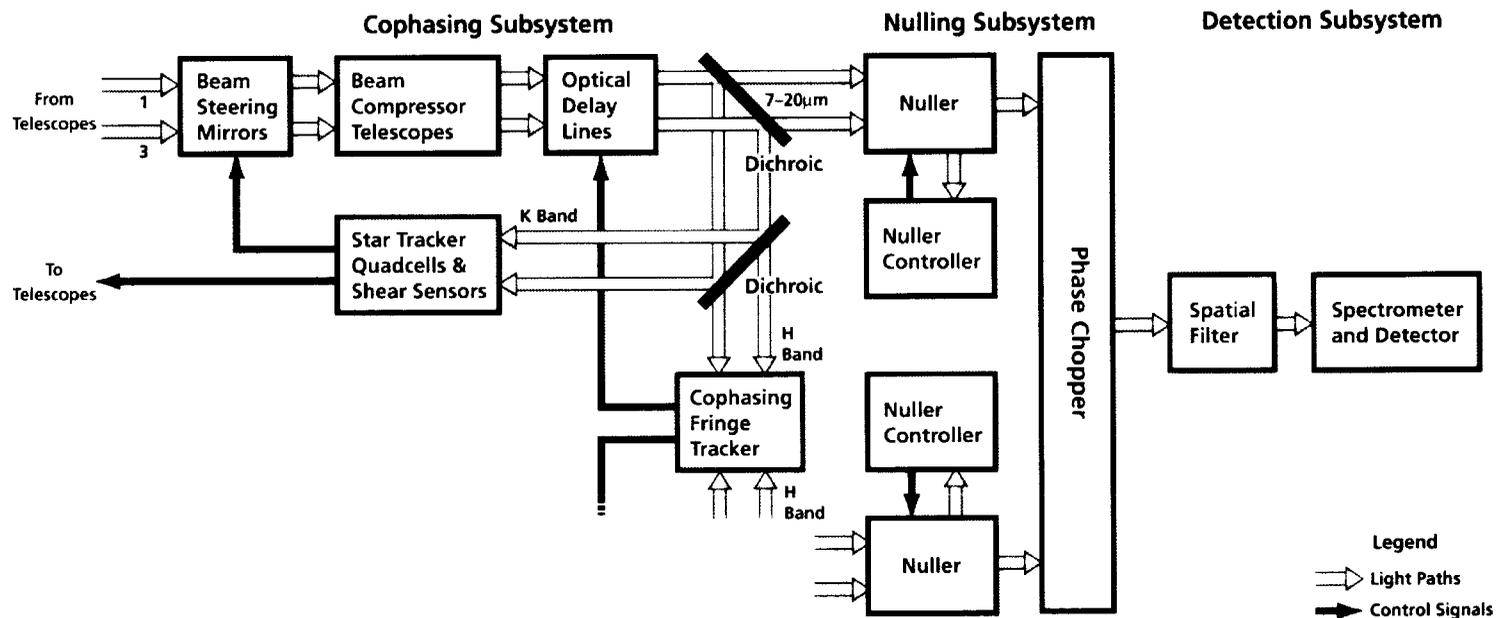
Achromatic Nulling Testbed

- Stable 10^{-6} white light null with 50% bandwidth
- 7-12 μm



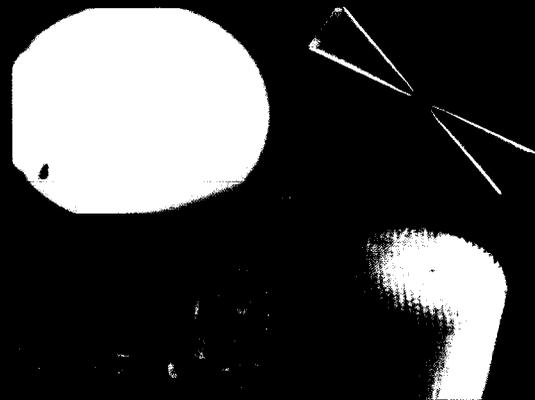
Planet Detection Testbed

- 4-beam demonstration of dual-chopped Bracewell
 - Planet extraction (10^{-6} planet/star contrast), laser
 - 10^{-6} null depth
 - 10^{-7} null stability
 - Amplitude and phase control

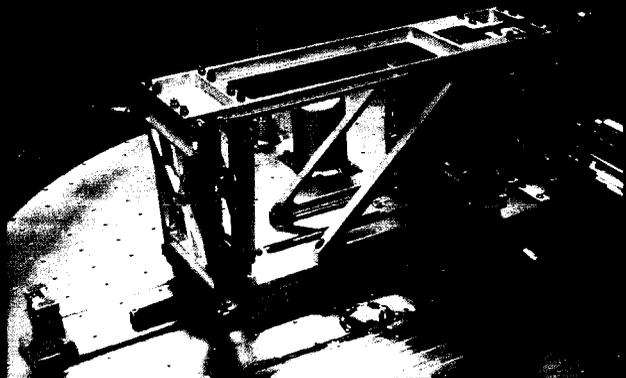


Core Interferometer Technology

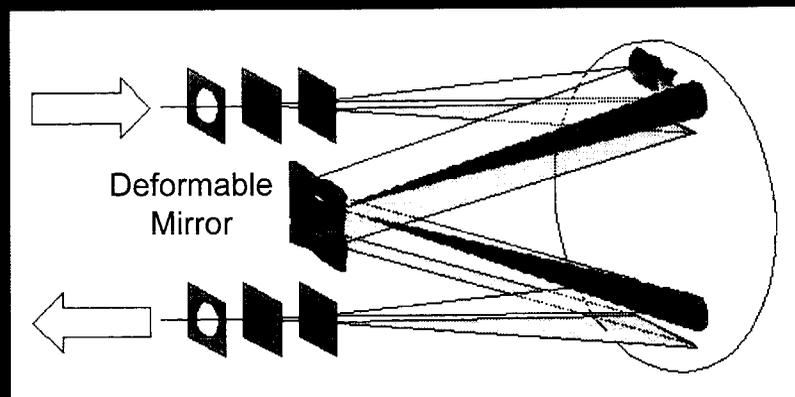
Mid-Infrared Spatial Filters



Cryogenic Delay Line



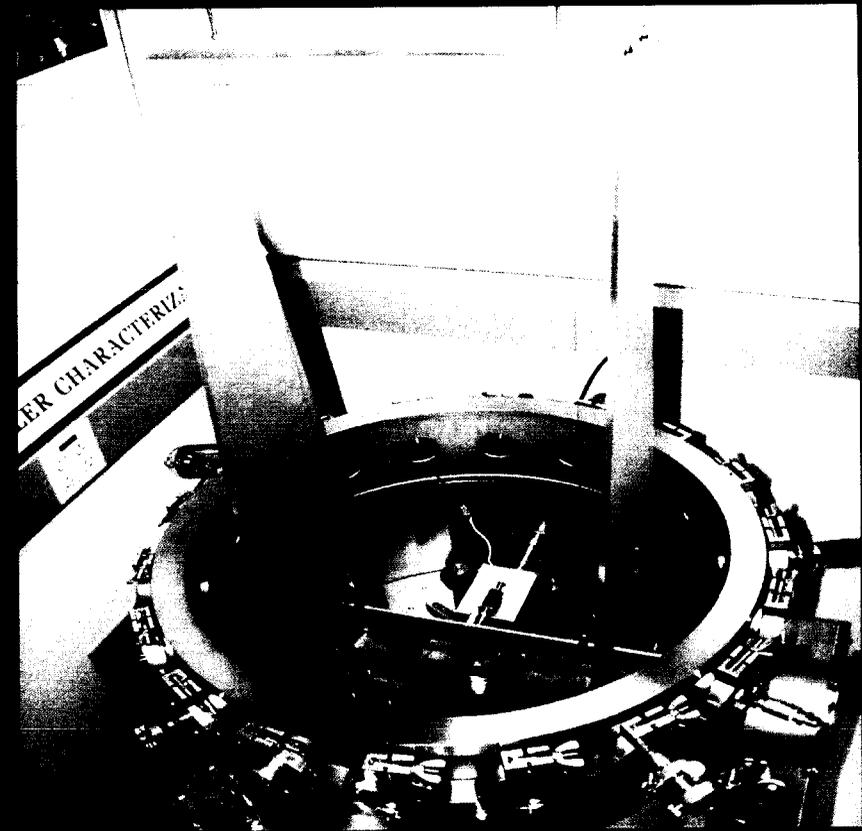
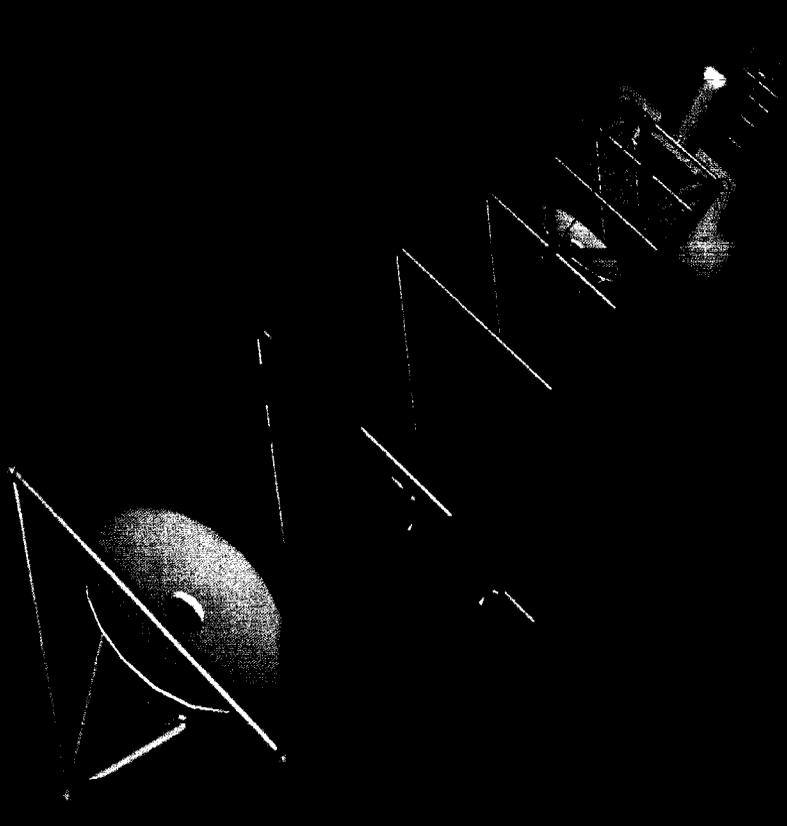
Adaptive Nuller



Cryogenic Structures Technology

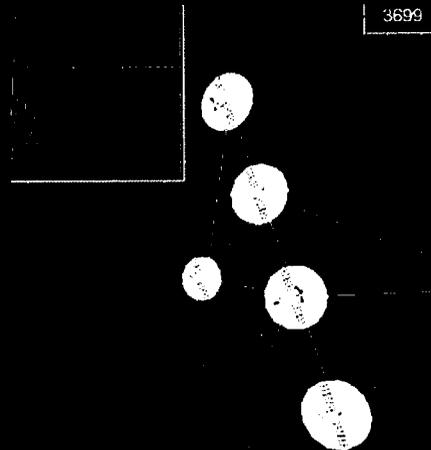
Structurally-Connected
Interferometer Testbed

Cryogenic Structures
Technology

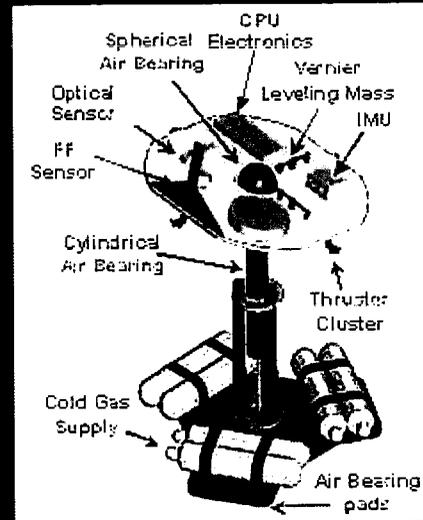


Formation Flying Technology

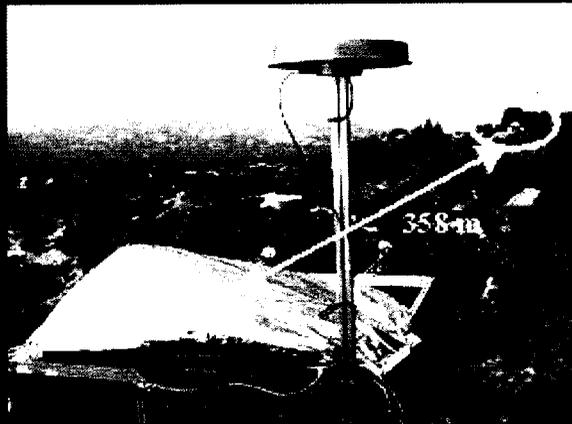
FAST



Formation Control Testbed



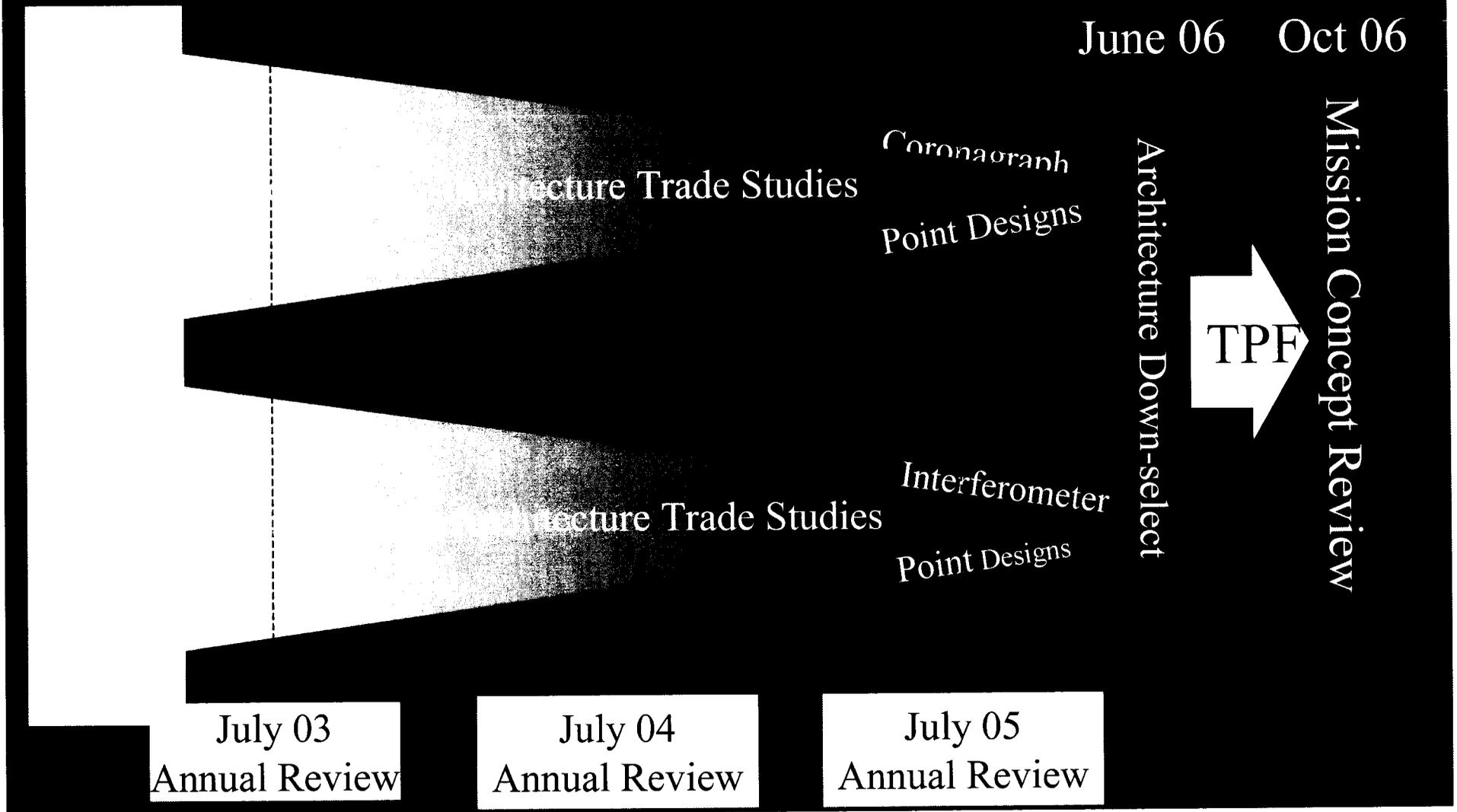
Formation Sensor Testbed



MIT Spheres



Selection of Final Architecture



Overriding goal: Find one design that is scientifically compelling and technologically ready for 2008 NAS Decadal Review and 2015 launch